The Thermal State of Accreting White Dwarfs

and What It Tells Us About the Evolution of Compact Binaries

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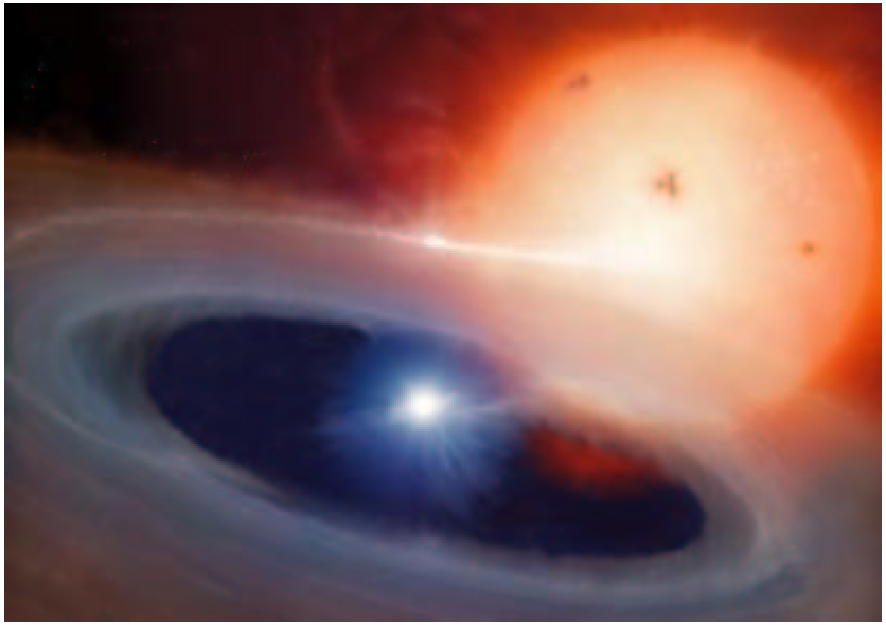
(Ph.D. work performed with Lars Bildsten, U.C. Santa Barbara)

Outline

- Accreting WD Thermal State essential for:
  - Testing Interruped Magnetic Braking – $\langle \dot{M} \rangle (t)$
  - Fully consistent classical nova ignition – $M_{\rm ign}$
  - Interpretation of spectral measurements – $T_{\rm eff}$
  - Late-time population properties – M_V
  - Accreting WD Seismology – M, $M_{\rm acc}$
- Context: Cataclysmic Variables
- Quasi-Static Model of Accreting WD
- The equilibrium T_c
- Comparisons with Observations – $T_{\rm eff}$, $M_{\rm ign}$, CN rate
- Seismology

Cataclysmic Variables



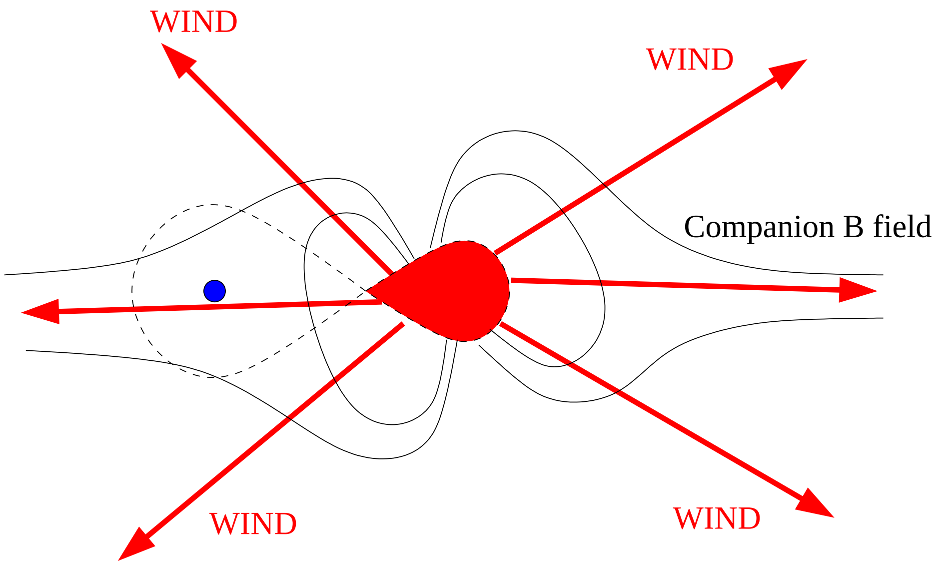
WD with low mass star companion in Roche lobe contact.
Exhibit outbursts:

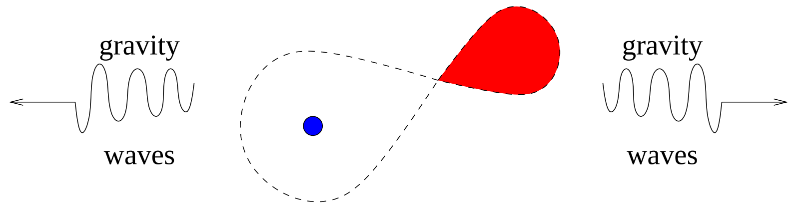
Classical Nova – Thermonuclear explosion on WD
recur $\sim 10^4 - 10^6$ yr

Dwarf Nova – Accretion disk “high” state
recur $\sim 0.1 - 10$ yr

Angular Momentum Loss

Evolution of tight binaries determined by loss of angular momentum: $\dot{J}$





Gravitational Radiation

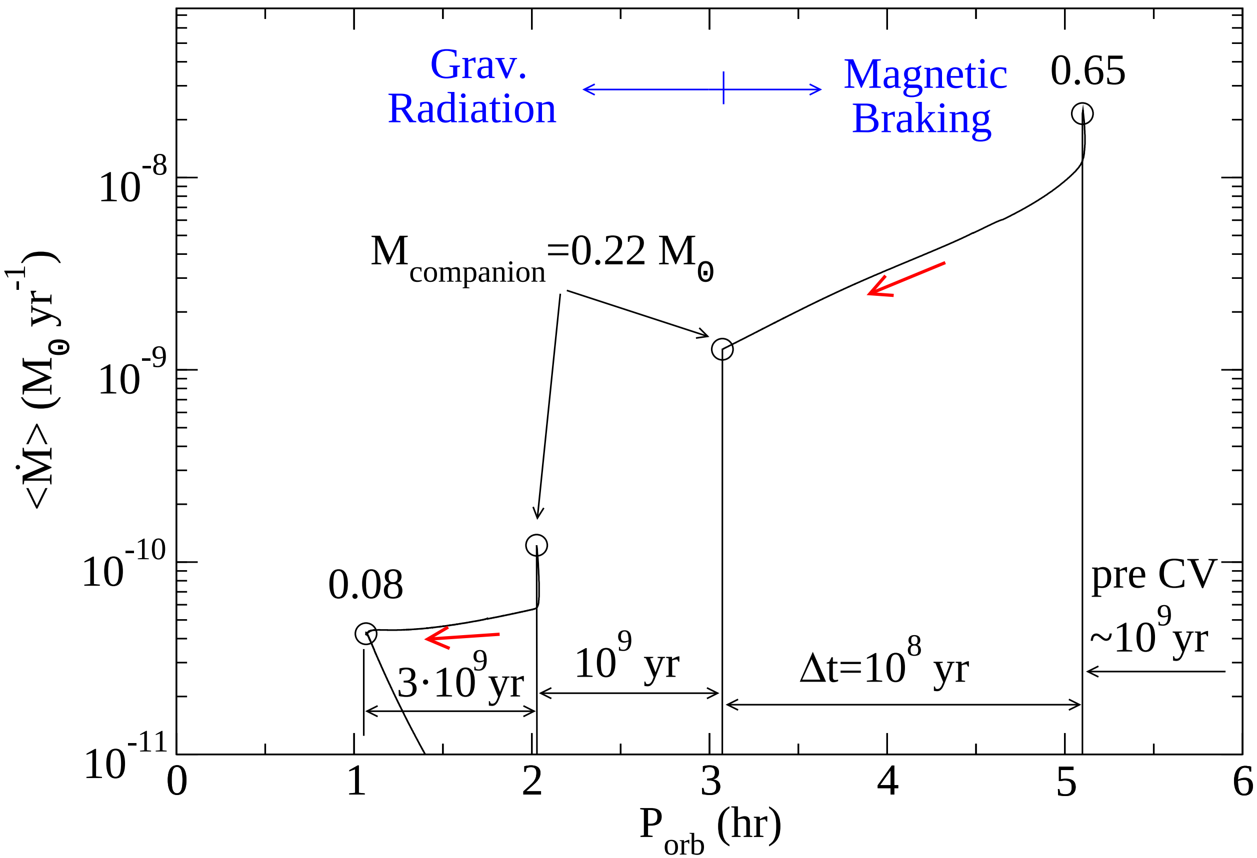
Magnetic Braking

magnetically attached wind from companion star

long $P_{\rm orb}$, high $\dot{J}$

short $P_{\rm orb}$, low $\dot{J}$

Interrupted Magnetic (Wind) Braking?



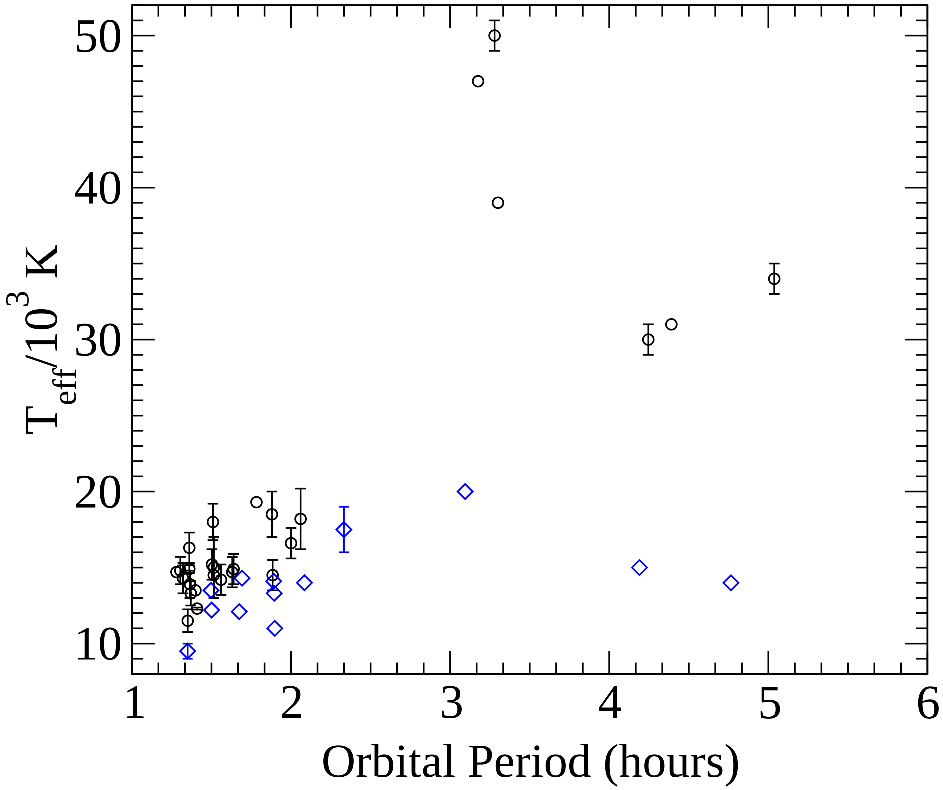
Open Questions:

- Is Mag. Braking prescription right?
- Does this fit observed population?

We can test this!

$M_{\rm WD} = 0.7 M_\odot$, Howell, Nelson, & Rappaport 2001, ApJ 550, 897

Measurements of WD $T_{\rm eff} \Rightarrow \langle \dot{M} \rangle$



○ Dwarf Nova Systems
◇ Magnetics

Townsley & Gänsicke, in preparation

UV measurements (HST, IUE) During DN quiescence

(e.g. Howell, Gänsicke, Szkody, & Sion 2002, ApJ, 575, 419)

Thermal emission sensitive to $\dot{M}$ averaged over the thermal time of the radiative envelope (~ 1000 yr)

Can inform our understanding of CV population and evolution

CV WD Environment

Observed timescales in Dwarf Nova (Disk outburst):

Disk Outburst:	lasts days-weeks
Between Outbursts:	month-years
Envelope Thermal time:	10^3 yr

Timescales in Classical Nova (Thermonuclear outburst):

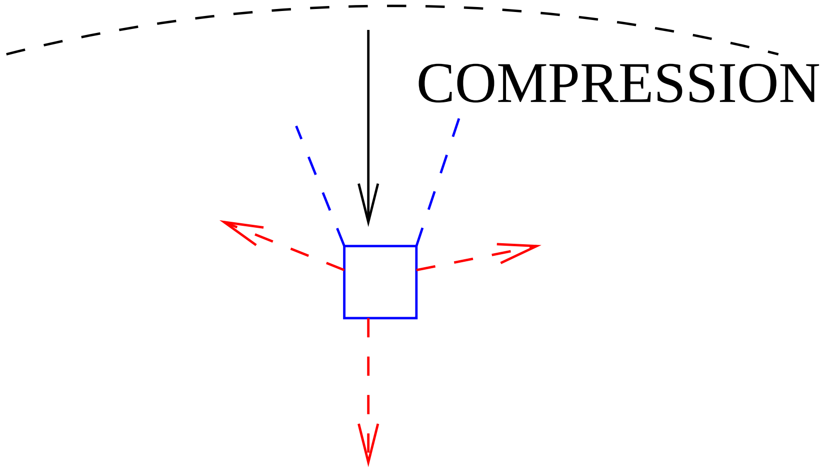
Outburst:	lasts < 10 years
Between Outbursts:	10^5 – 10^7 years

Using $\langle \dot{M} \rangle$: The time averaged accretion rate
We have calculated

$$M, \langle \dot{M} \rangle \quad \rightarrow \quad T_{\rm eff}, M_{\rm ign}$$

which connects the WD evolution to that of the binary.

Gravitational Energy Release

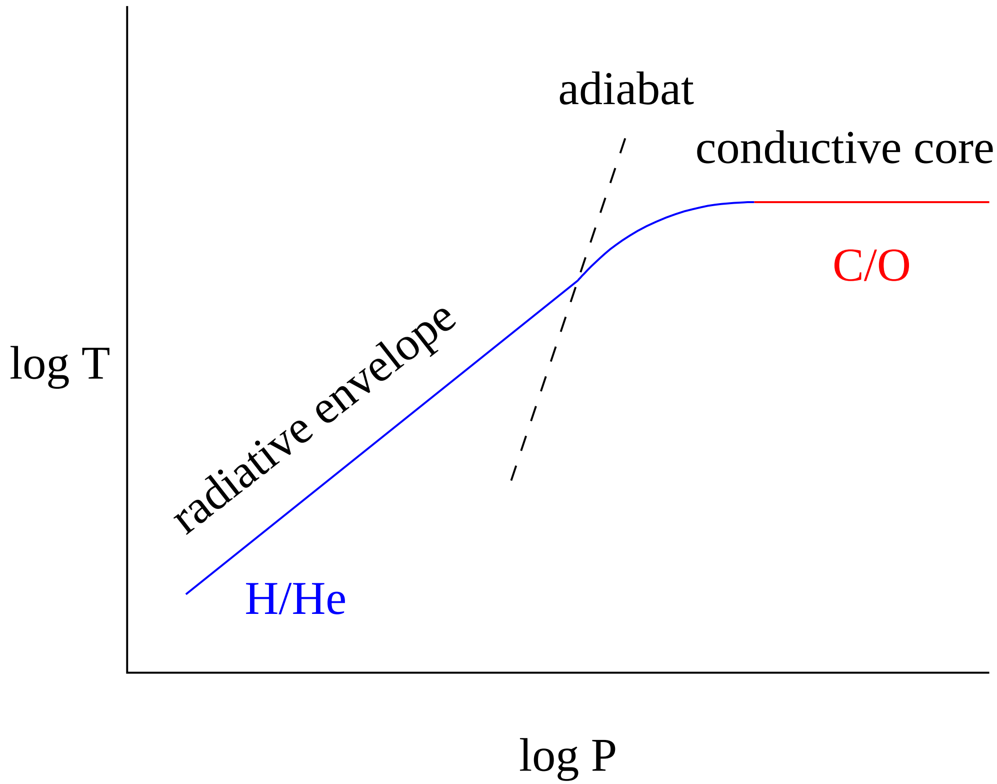


$$t_{\rm th} \equiv \frac{\Delta M c_P T}{L} \quad < \quad t_{\rm acc} \equiv \frac{\Delta M}{\langle \dot{M} \rangle}$$

Heat liberated by compression

transferred out to surface
in to core
"compressional heating"

Quasi-static Model



Heat Equation:

$$v_r = -\langle \dot{M} \rangle / 4\pi r^2 \rho$$

0 static

$$T\frac{Ds}{Dt} = T\frac{\partial s}{\partial t} + T v_r \frac{\partial s}{\partial r} = -\frac{dL}{dM_r} + \epsilon_N$$

Envelope Dominates

$$\frac{\langle \dot{M} \rangle}{4\pi r^2 \rho} T \frac{\partial s}{\partial r} = \frac{dL}{dM_r} + \epsilon_N$$

Without ϵ_N, $dr = g\rho dP$

$$L = -\langle \dot{M} \rangle \int_0^P T \frac{\partial s}{\partial P} \, dP$$

Simple integration to $M_{\rm acc} \sim 10^{-3} M_\odot$

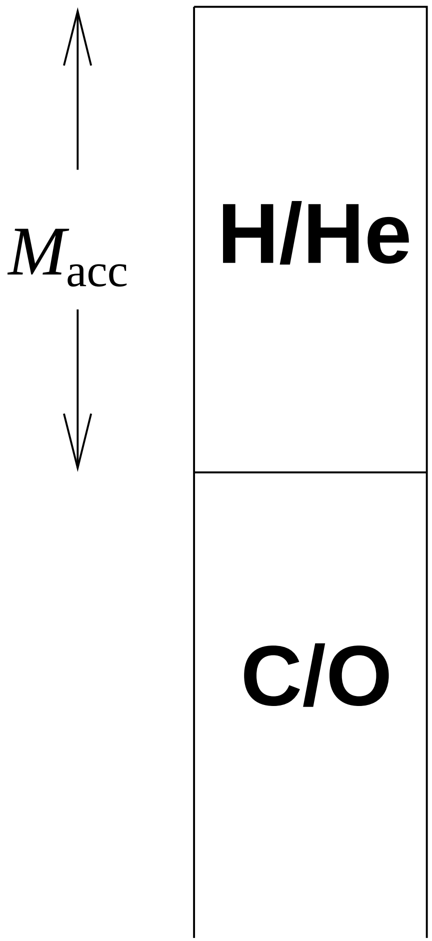
$$L_{\rm H/He} \approx 2.5 \frac{kT_c}{\mu m_p} \langle \dot{M} \rangle \qquad L_{\rm C/O} \approx 16 \frac{kT_c}{\mu_i m_p} \langle \dot{M} \rangle$$

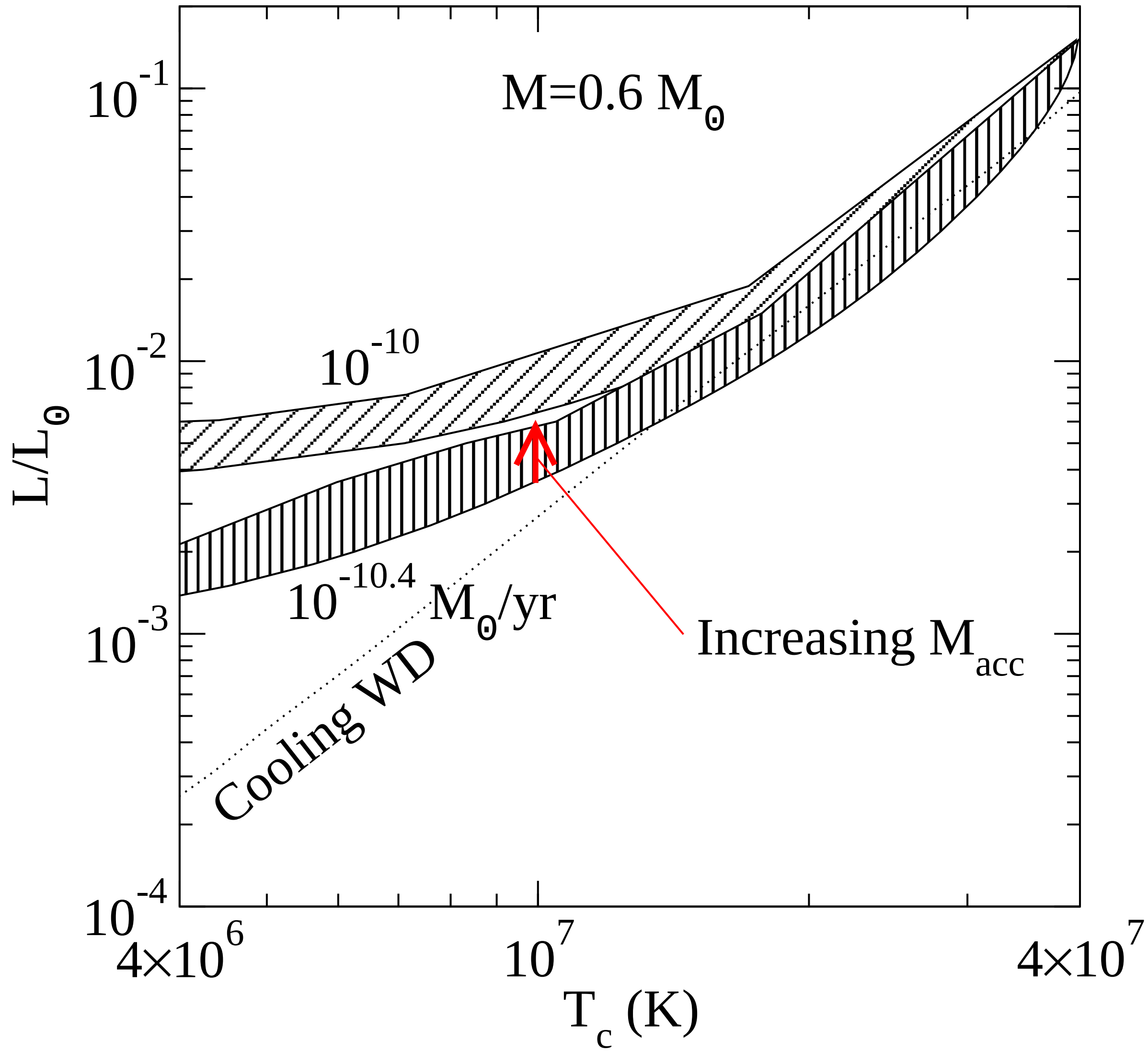
$\mu =$ mean molecular weight

with $\mu \simeq 0.6$ and $\mu_i \simeq 14$

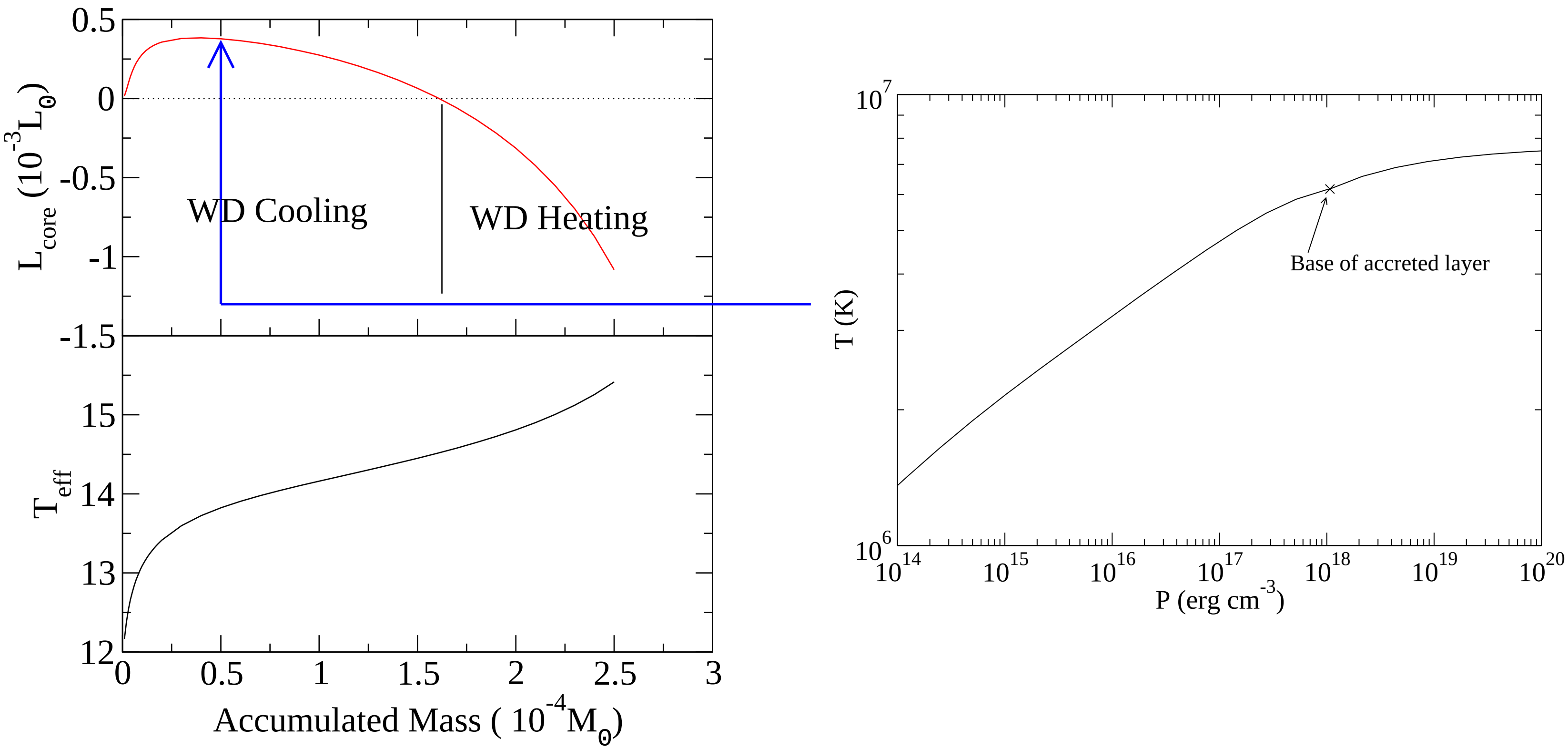
$$\frac{L_{\rm H/He}}{L_{\rm C/O}} \simeq 4$$

L dependence on T_c



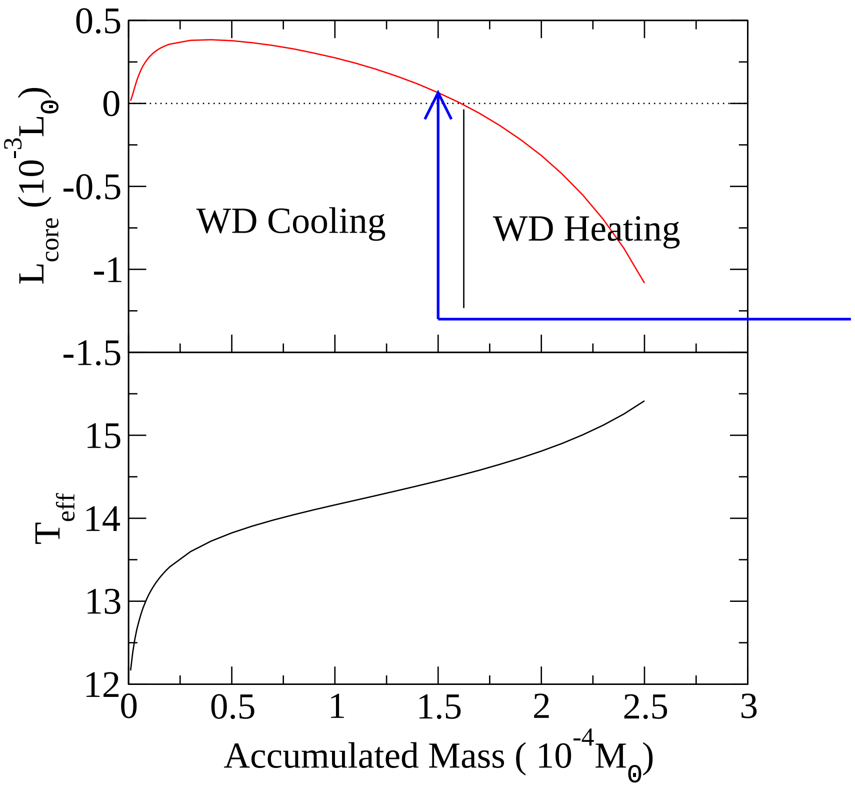


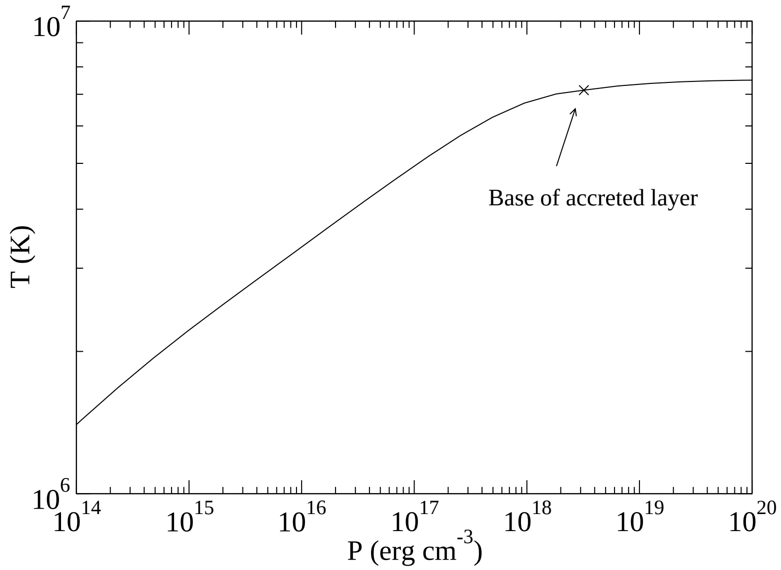
Cooling-Heating Cycle



- Core will be Reheated until equilibrium is reached.
  Core thermal time $\sim 10^8$ yr

Cooling-Heating Cycle





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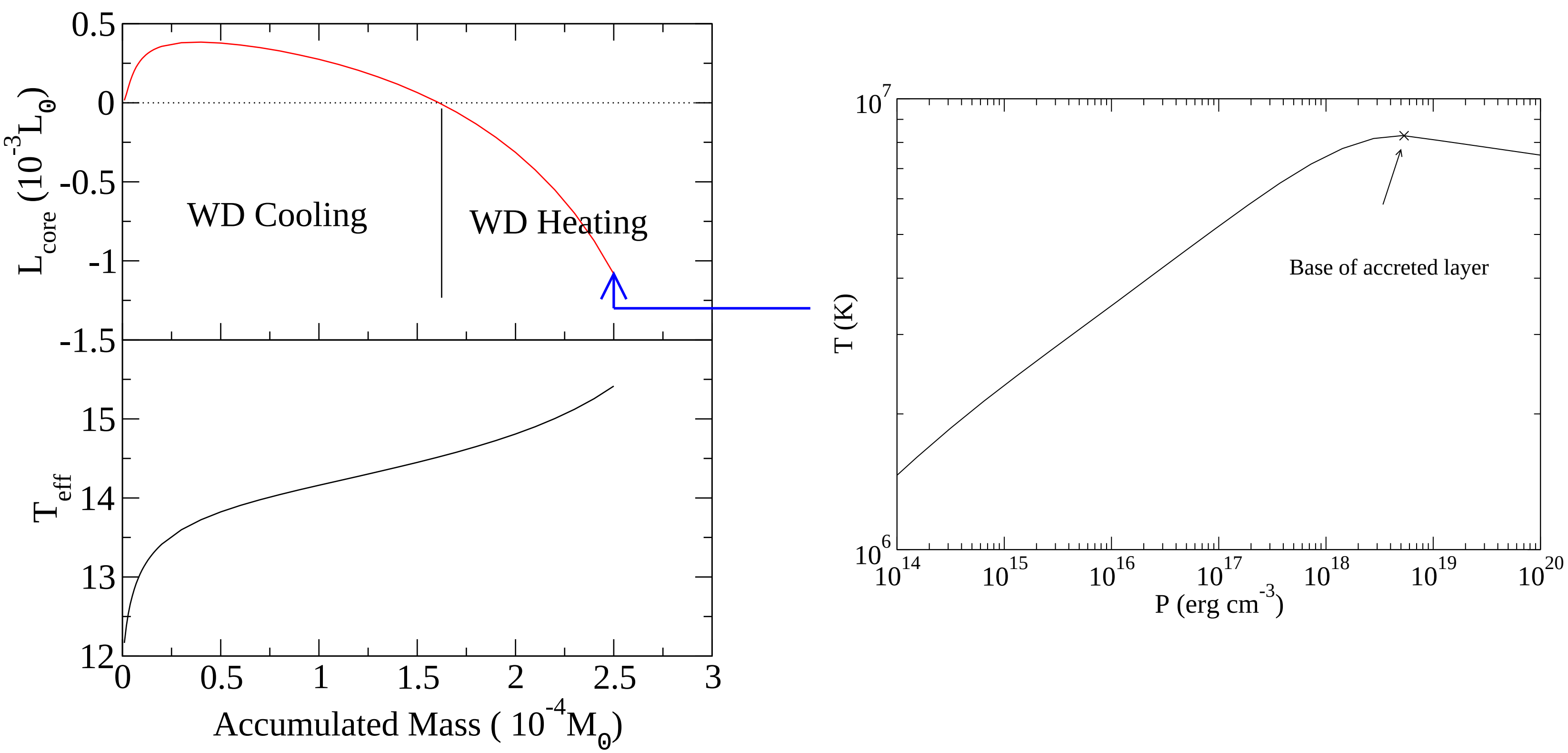

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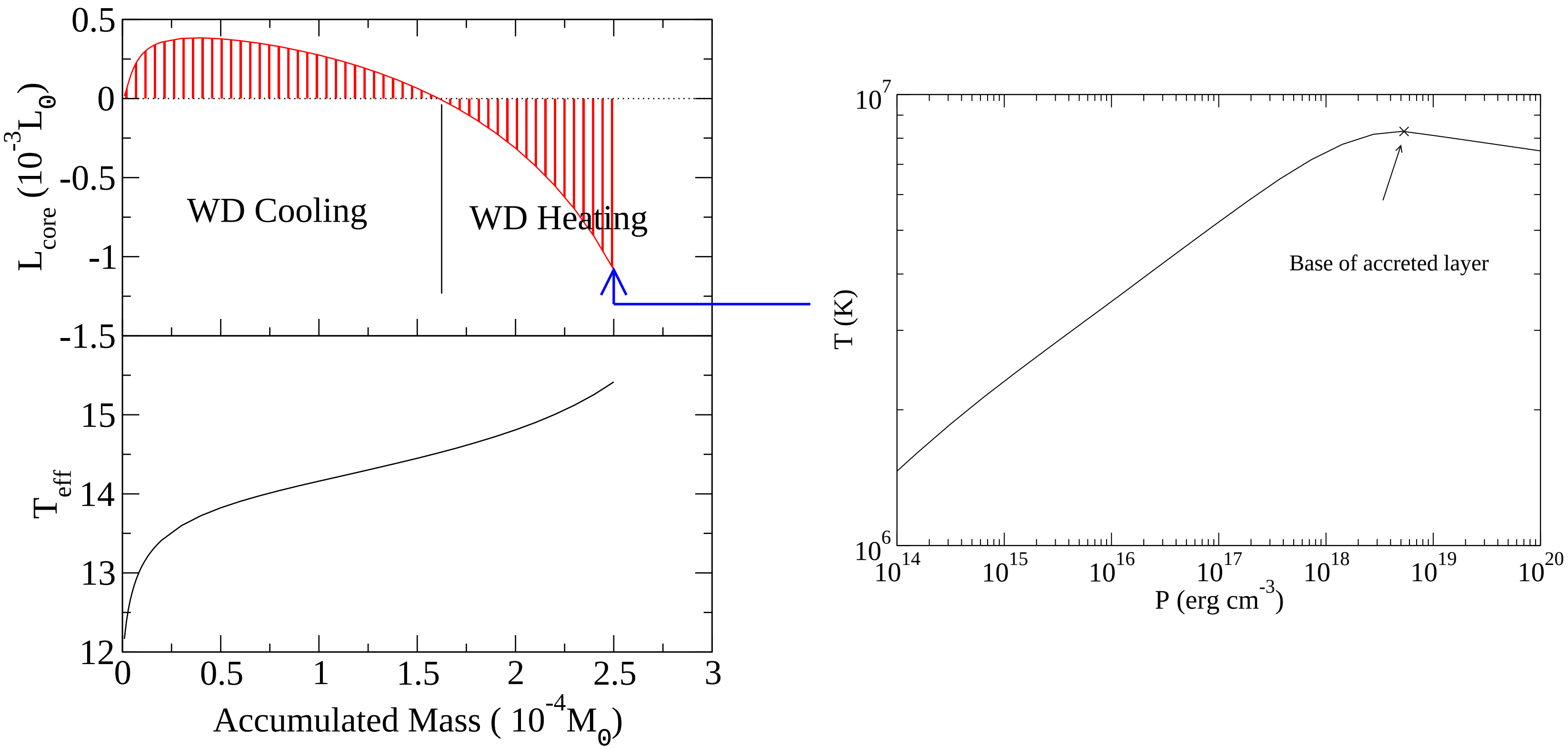

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$$\langle L_{\rm core} \rangle = \frac{1}{t_{\rm CN}} \int_0^{t_{\rm CN}} L_{\rm core}\, dt$$

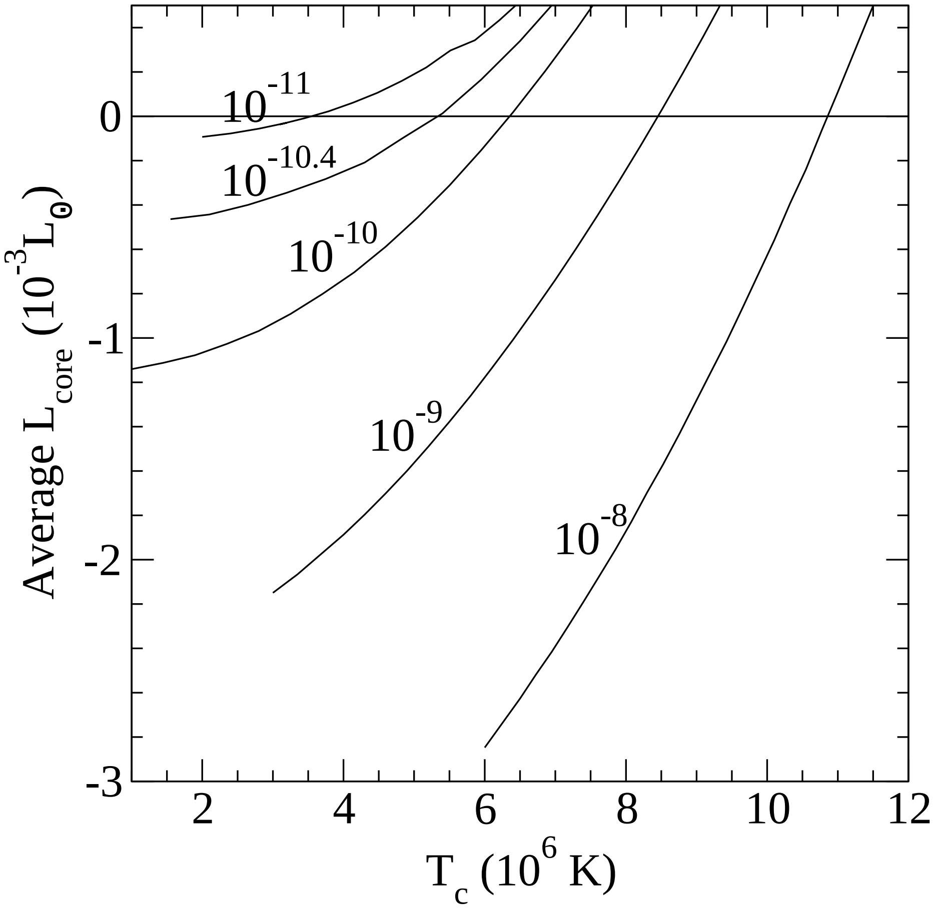
$\langle L_{\rm core}\rangle$ and the equilibrium T_c

$$\langle L_{\rm core}\rangle = \frac{1}{t_{\rm CN}}\int_0^{t_{\rm CN}} L_{\rm core}\, dt$$

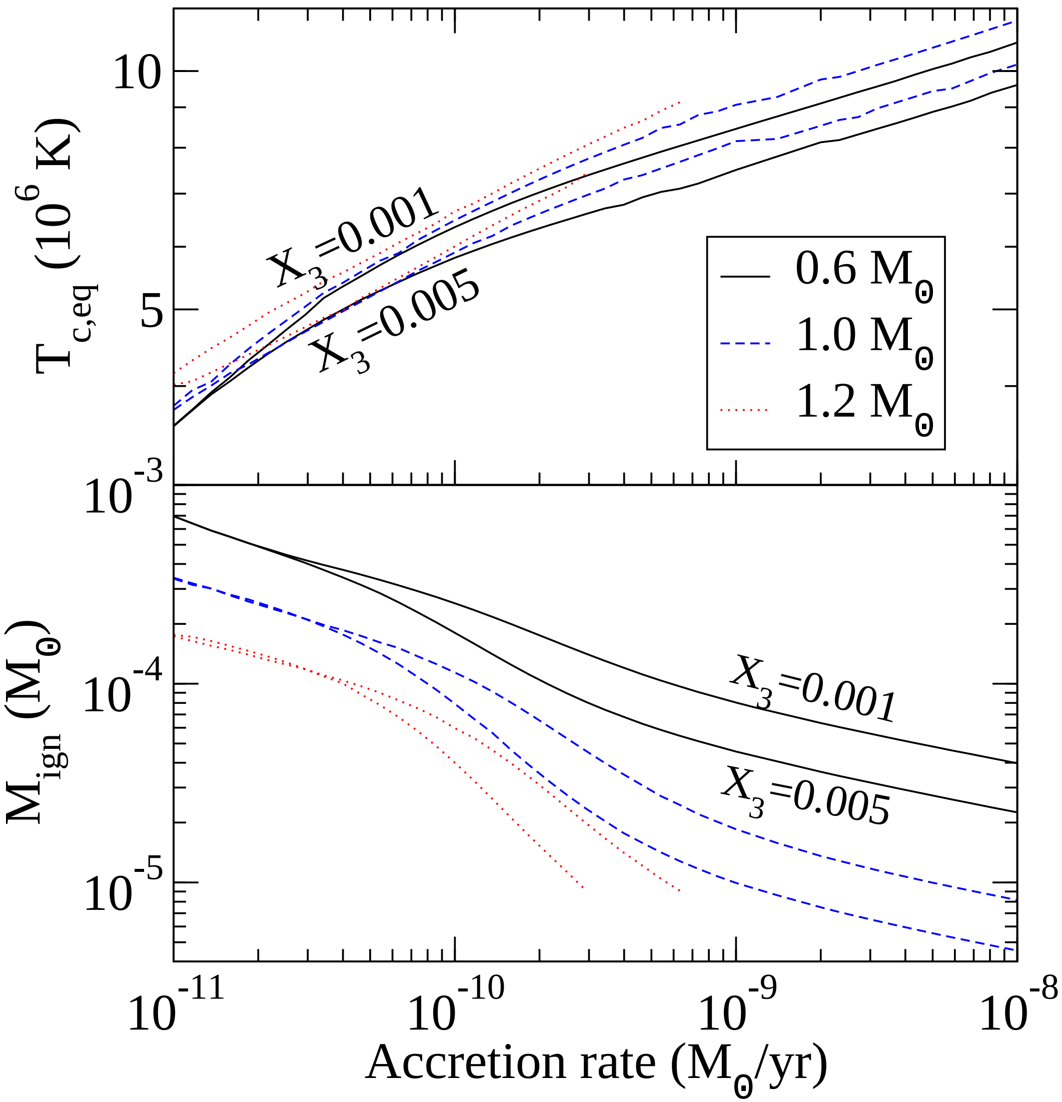
When $M_{\rm ej} = M_{\rm ign}$, $\langle L_{\rm core}\rangle = 0$ defines an

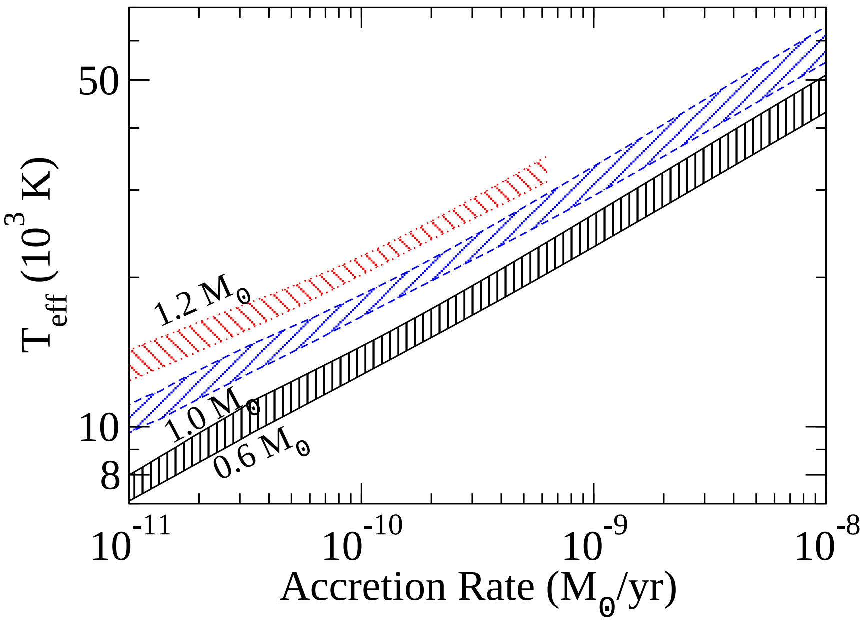
Equilibrium T_c

which is set by M and $\langle \dot{M}\rangle$



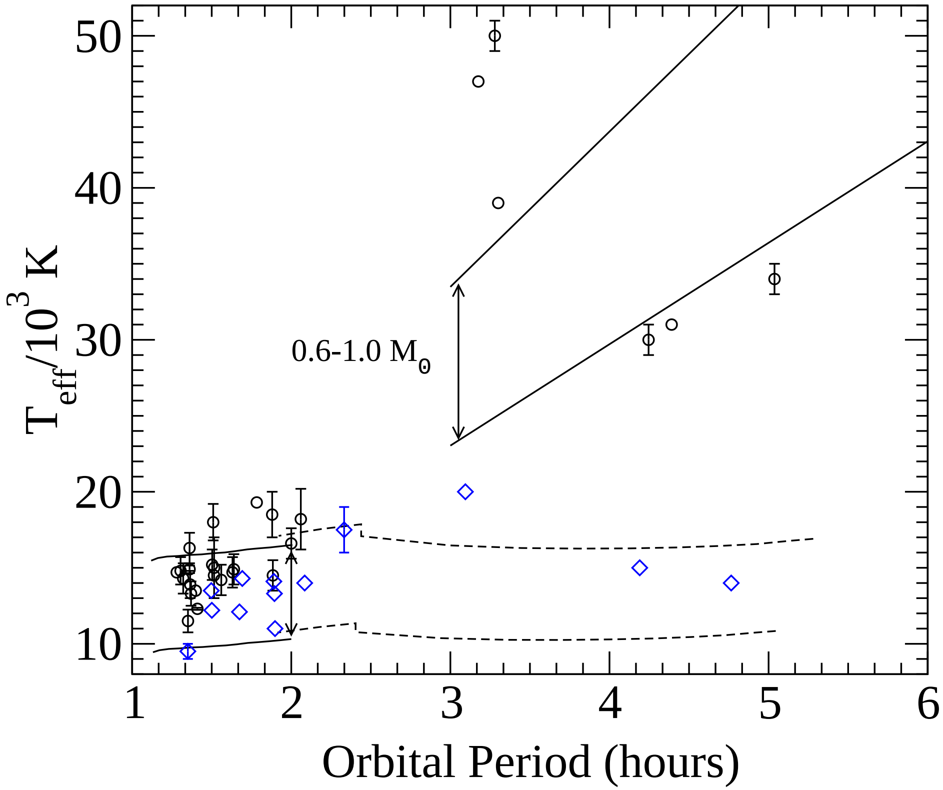
Equilibrium $T_c \rightarrow M_{\rm ign}, T_{\rm eff}$





$X_3 =$ mass fraction of ^{3}He in accreted material

$T_{\rm eff}$ vs. $P_{\rm orb}$



○ Dwarf Nova Systems

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Townsley & Gänsicke, in preparation

Theory range shown: 0.6-1.0$M_\odot$

Factor of $\sim 10 \langle \dot{M} \rangle$ contrast across period gap confirmed

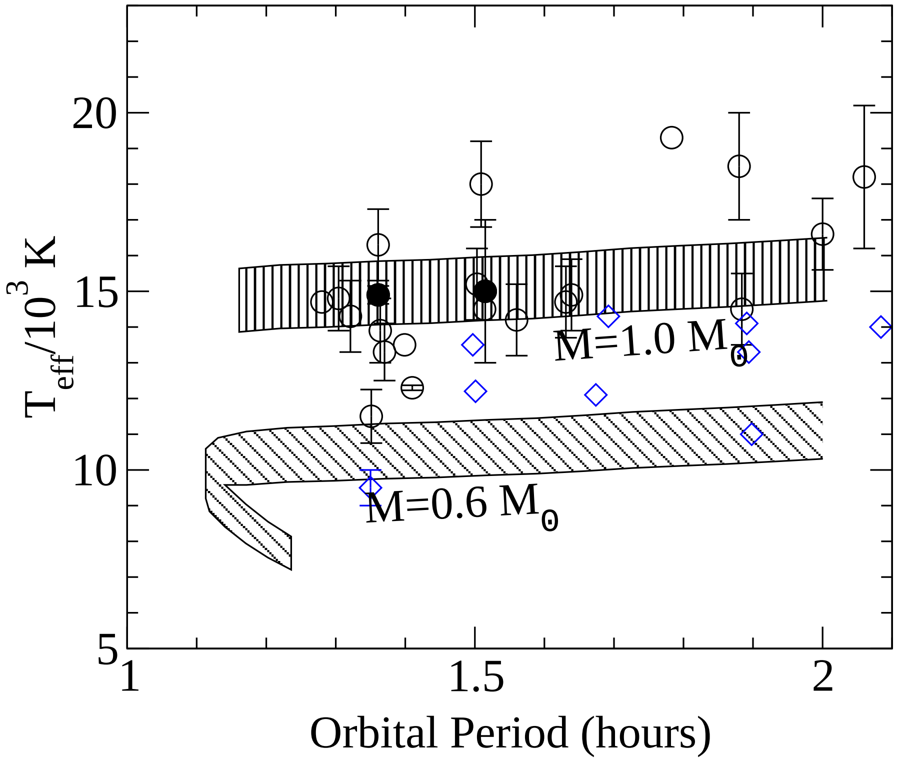
Current Mag. Braking prescription matches well with DN at 4-5 hours

Separate population of high $\langle \dot{M} \rangle$ at 3 hours?

Magnetic CVs above gap near Grav. Radiation prediction
– WD magnetic field preventing magnetic braking?!

(Li, Wu, & Wickramasinghe 1994, MNRAS, 268, 61)

$T_{\rm eff}$ vs. $P_{\rm orb}$ Below Gap



$\dot{J}$ from GW,

Kolb & Baraffe 1999, MNRAS, 309, 1034

Filled points,

$$M = \begin{matrix} 0.9 \pm 0.15 \\ 0.82 \pm 0.05 \end{matrix} \; M_\odot$$

M average of 0.76 expected from selection,

Dünhuber & Ritter 1993

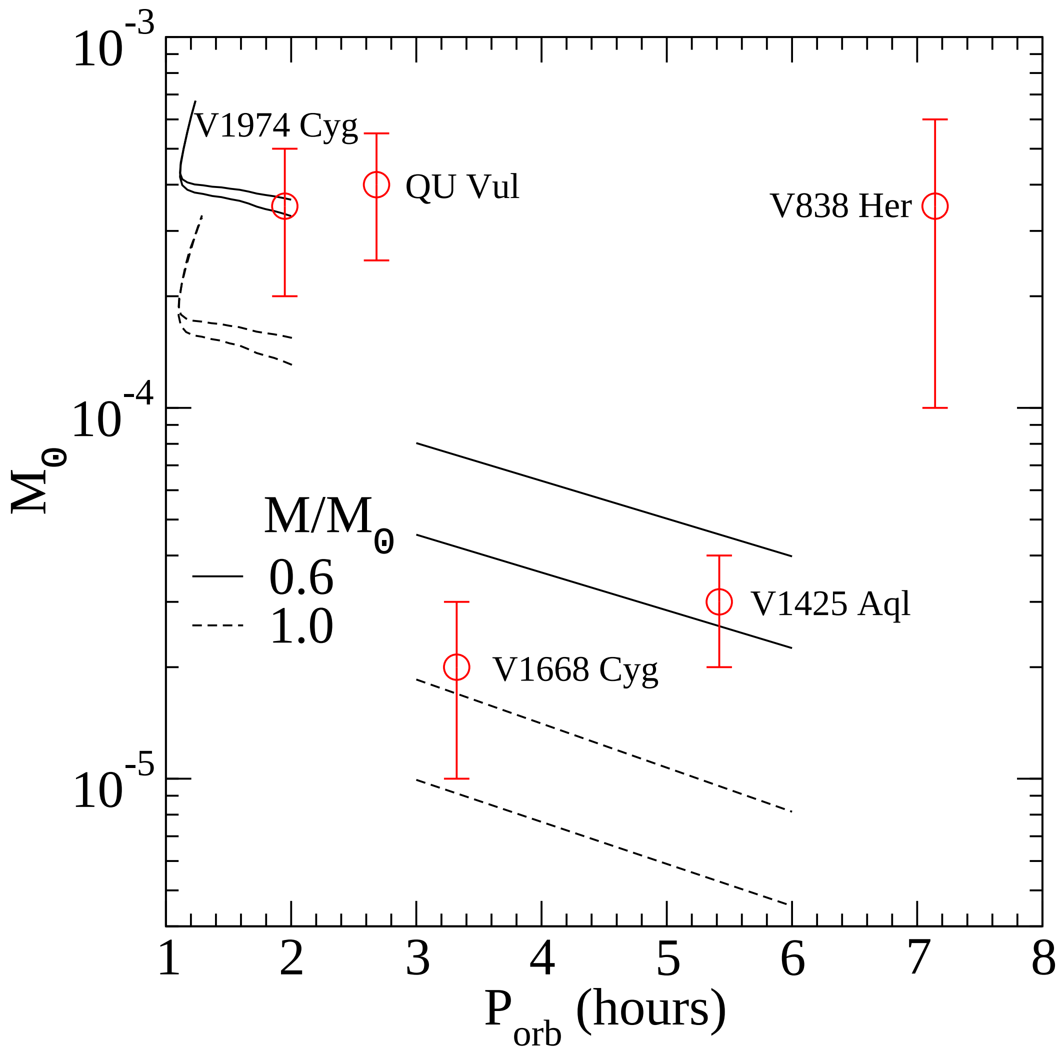
M is surprisingly consistent

Likely $\langle \dot{M} \rangle > \langle \dot{M} \rangle_{GW}$, but only by small amount

Magnetics appear to have slightly lower $\langle \dot{M} \rangle$

Theoretical $P_{\rm min}$ well-known outstanding problem

Self Consistent $M_{\rm ign}$

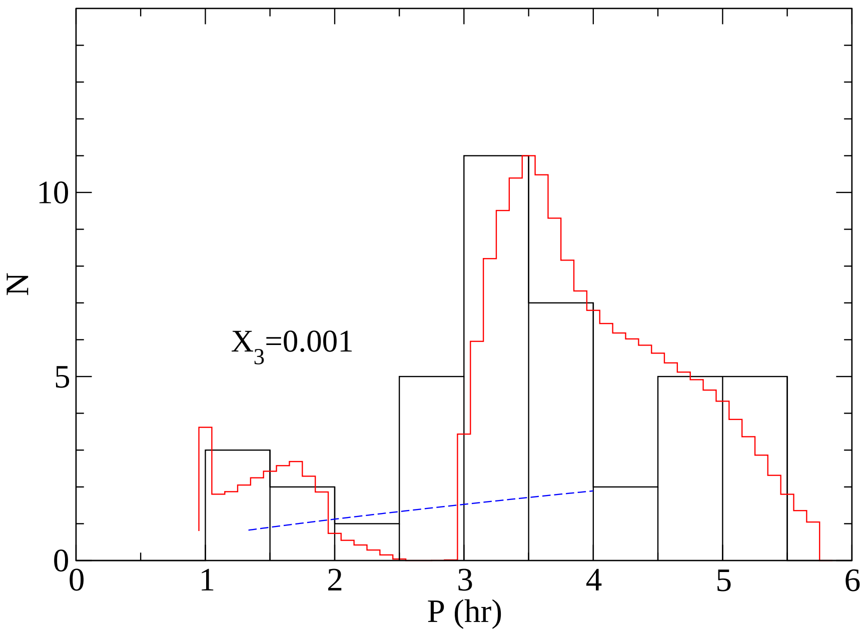


Data points are $M_{\rm ej}$ for systems with $P_{\rm orb}$ also measured, various sources.

Lines are our $M_{\rm ign}$ with $\langle \dot{M} \rangle$ from magnetic braking (3-6 hours) and grav. rad. (< 2 hours)

Consistent with $M_{\rm ej} = M_{\rm ign}$, but not conclusive

Classical Nova $P_{\rm orb}$ Distribution



Theory curve uses Interrupted Magnetic Braking for

$$P_{\rm orb} \quad \rightarrow \langle \dot{M} \rangle$$

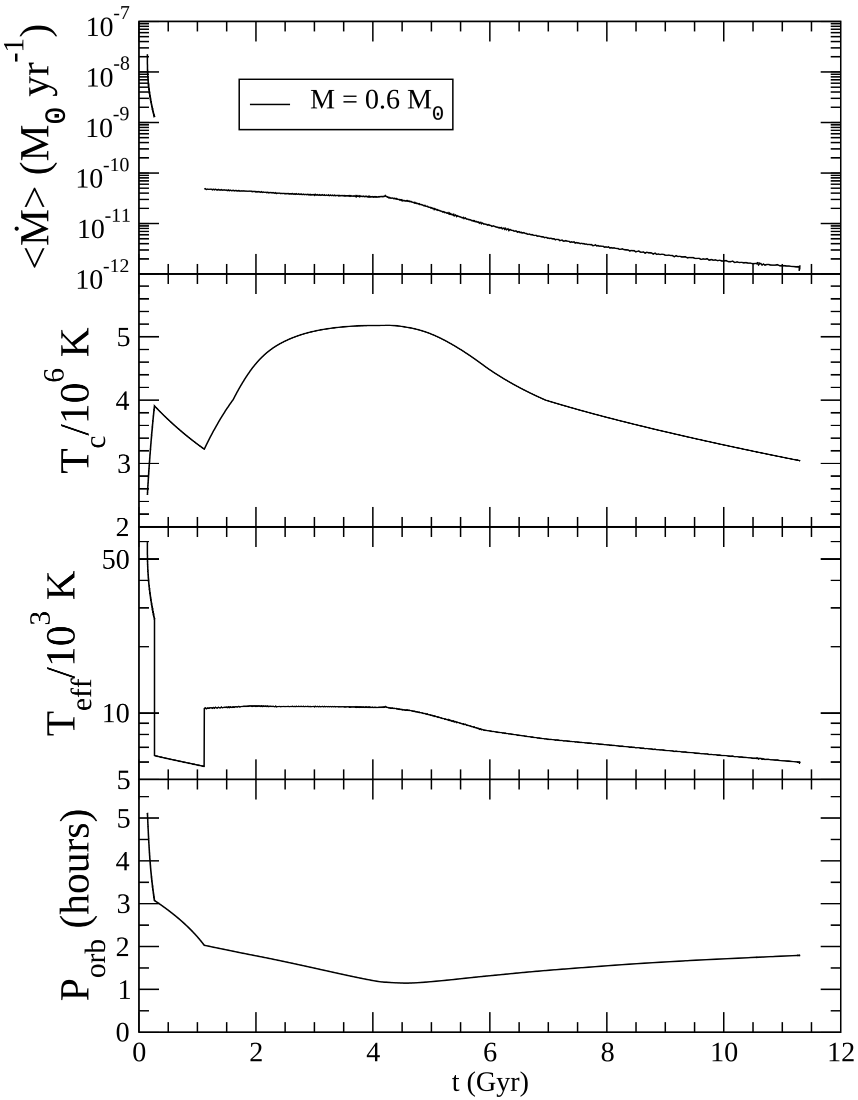
and population n_P

(Howell, Nelson, Rappaport 2001, ApJ 550, 897)

Our $M_{\rm ign}$ is used to calculate classical nova rate assuming average $M = 1.0 M_\odot$

- Again supports a factor of > 10 drop in $\langle \dot{M} \rangle$ across gap
- Consistent with idea that CVs evolve across the gap
- Possible population of magnetic systems filling in gap
- Ignores selection effects – hard to quantify

WD Thermal State Evolution



Phases of accretion

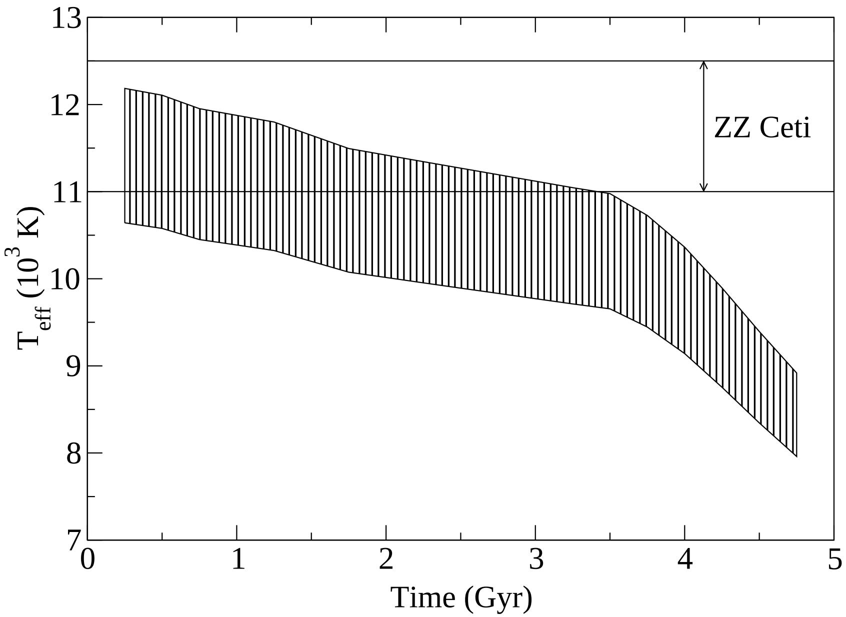
1. Magnetic Braking $\langle \dot{M} \rangle \sim 5 \times 10^{-9} M_\odot$ yr^{-1}
2. Period gap $\langle \dot{M} \rangle = 0$
3. Gravitational radiation $\langle \dot{M} \rangle \simeq 5 \times 10^{-11} M_\odot$ y
4. Post-period minimum $\langle \dot{M} \rangle < 10^{-11} M_\odot$ yr^{-1}

Phases of WD evolution

1. Reheating – $T_{\rm eff}$ set by $\langle \dot{M} \rangle$
2. Equilibrium – $T_{\rm eff}$ set by $\langle \dot{M} \rangle$
3. Cooling – $T_{\rm eff}$ set by core cooling

Accretion resets the clock for WD coolin

Broadband Spectral Evolution

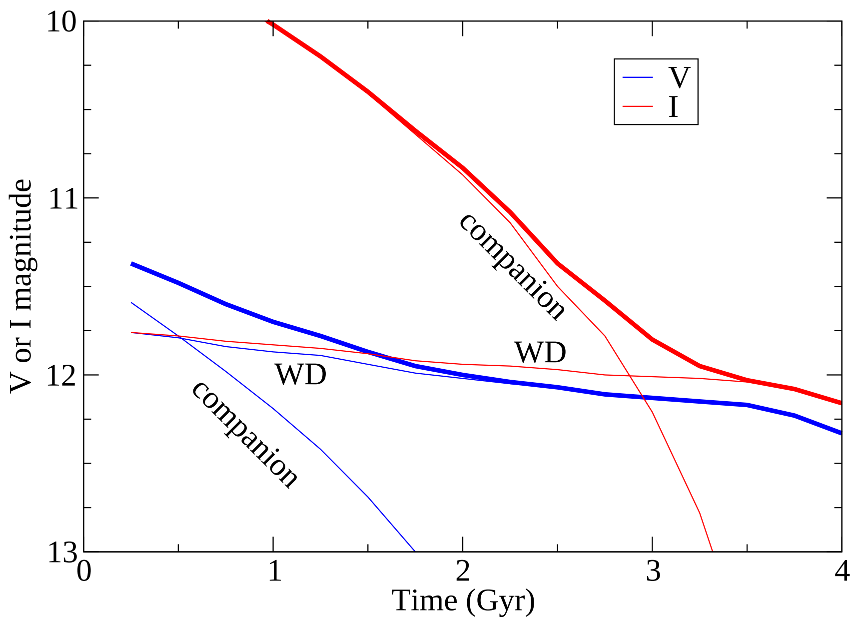


$M = 0.6 M_\odot$,

$\dot{J}_{\rm binary}$ from grav. waves

$\Longrightarrow \langle \dot{M} \rangle (t)$

(Kolb & Baraffe 1999, MNRAS, 309, 1034)



Transition from main sequence broadband fluxes to those of a WD.

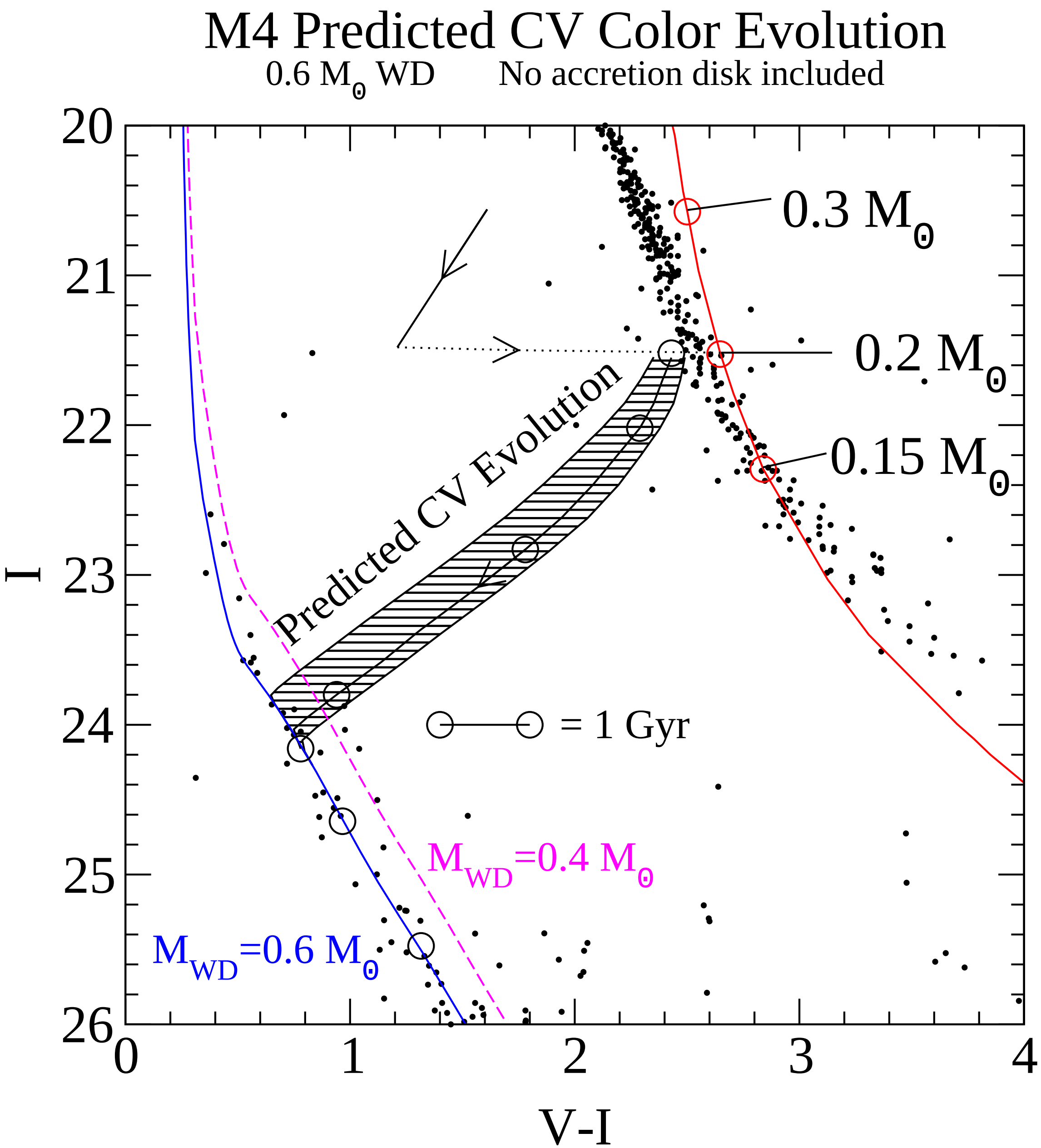
Companion Mag. from

(Brocato, Cassisi, & Castellani 1998, MNRAS, 295, 711);

WD Mag. from

(Bergeron, Wesemael, & Beauchamp 1995, PASP, 107, 1047)

Broadband CV Spectral Evolution

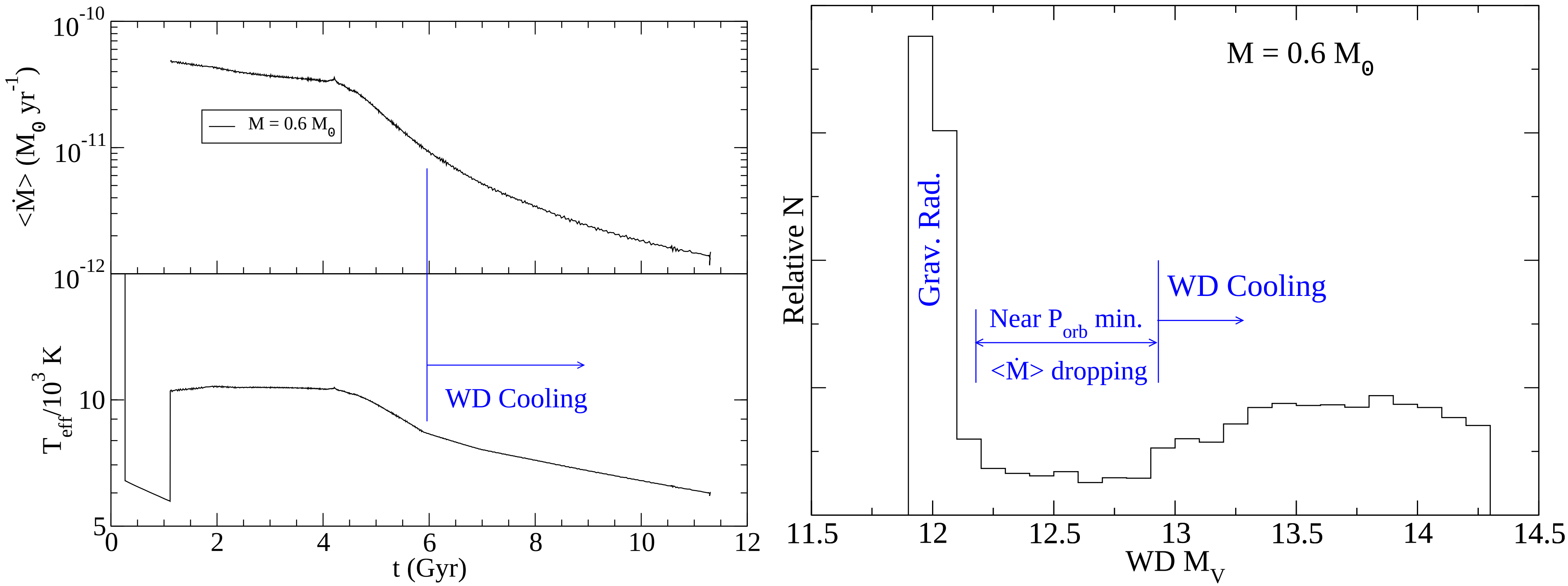


Proper-motion selected members of M4 at 4 core radii (Richer et al. 2002, ApJ, 574L, 151)

Color selection criteria for old CVs

CVs Mixed with WD population used to date cluster

Luminosity Function of Old CVs

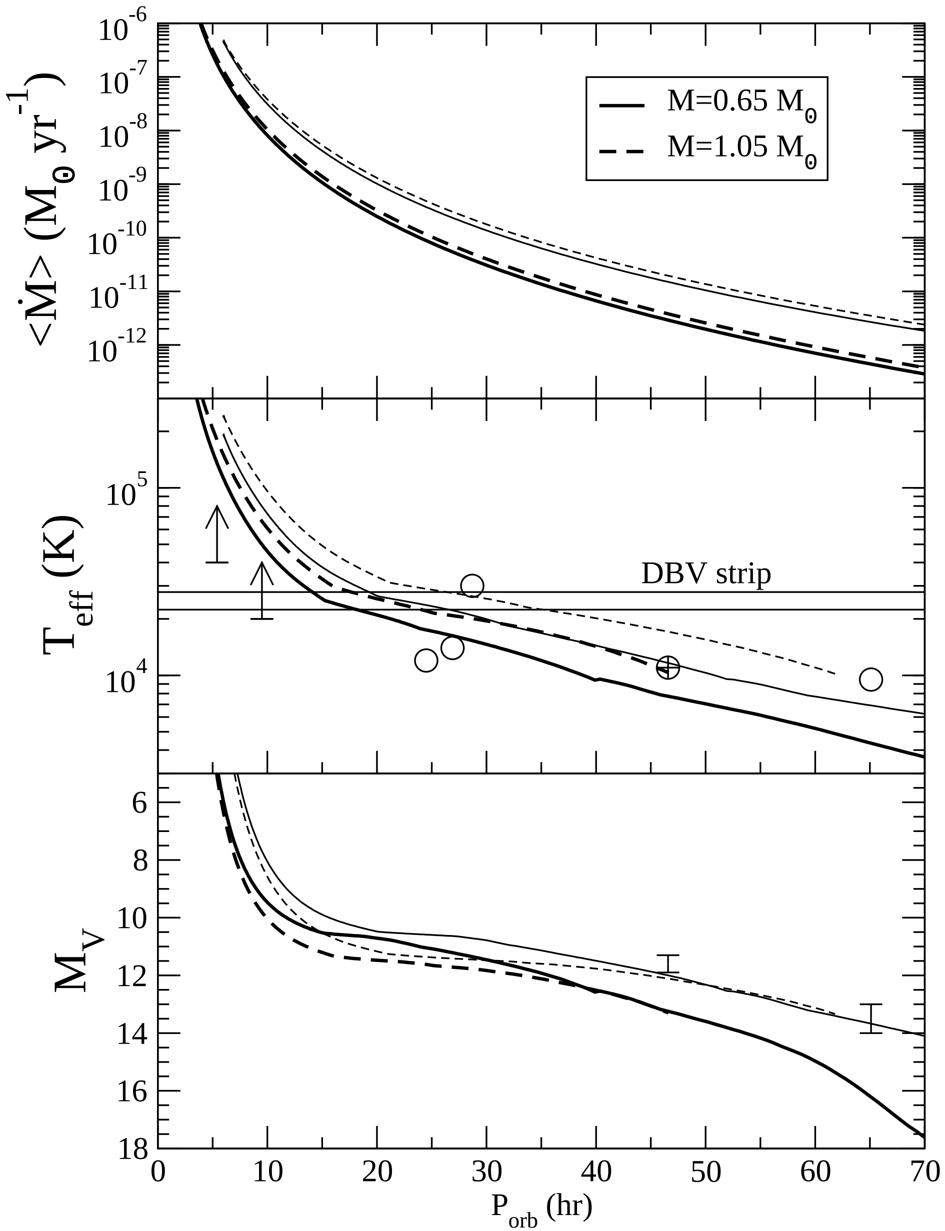


Low $\langle \dot{M} \rangle$ leads to infrequent disk outbursts

CV V magnitude dominated by WD

Most old CVs appear as cooling WDs until inspected carefully

Evolution of He Accretors (AM CVns)



WDs which accrete helium from a companion lower mass heilum WD

$\langle \dot{M} \rangle$ monotonically decreases with time as $P_{\rm orb}$ increases

Curves show 2 WD masses and 2 possible donor thermal states

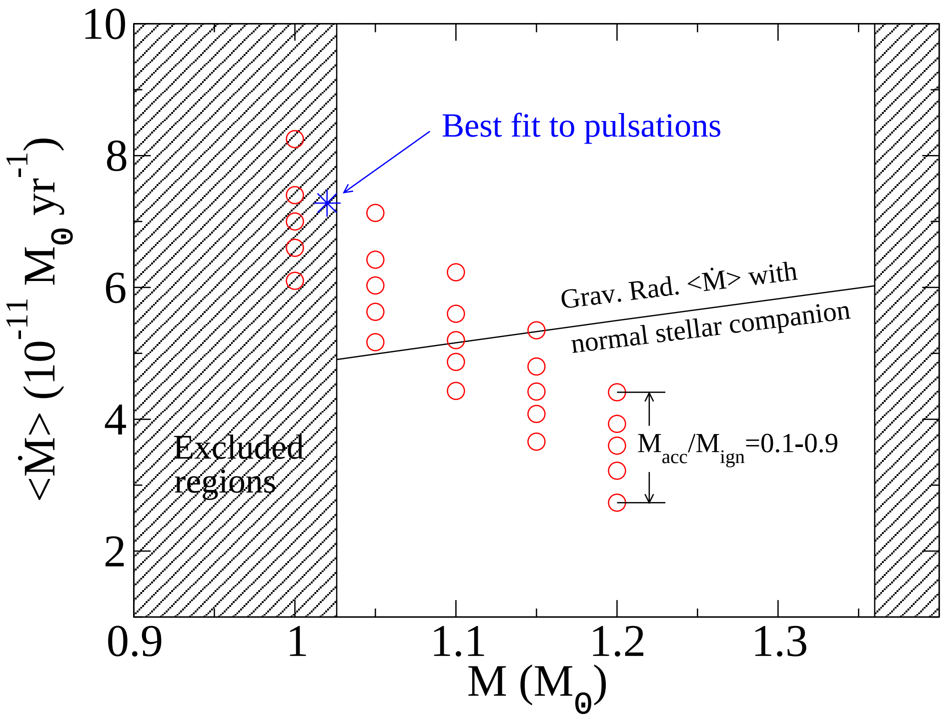
(Deloye & Bildsten 2003, ApJ, 598, 1217)

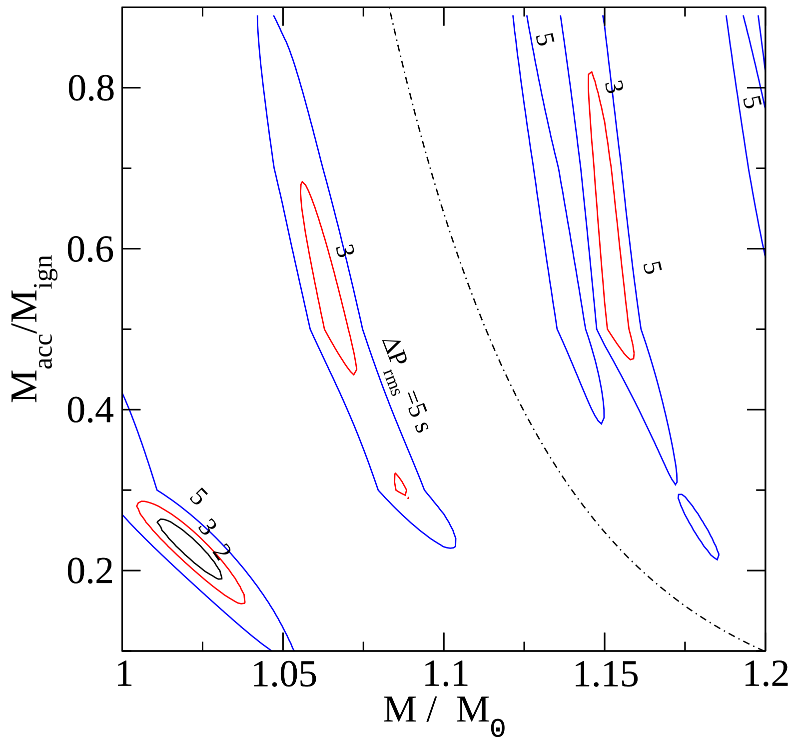
Similar evolution: reheating, equilibrium (short!), WD cooling

Accretion disk phenomenology not well understood, two-state (DN) accretion expected with increasing time spent in quiescence

Both measured M_V agree well with theory

Accreting WD Seismology





Distance broadly constrains M, $T_{\rm eff}$ relates $\langle \dot{M} \rangle$ and $M_{\rm acc}$

Only three modes observed, not well characterized

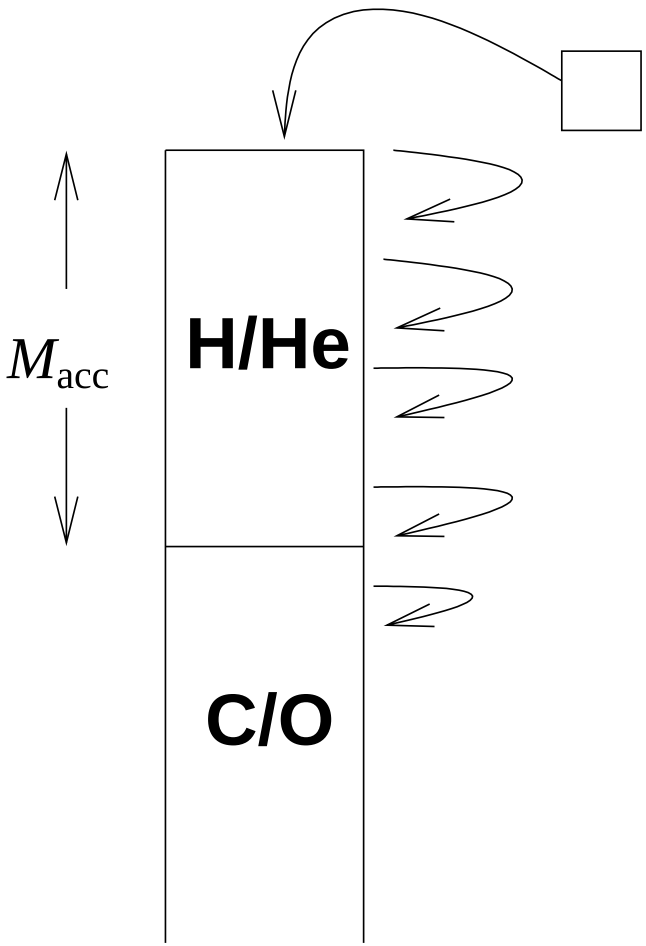
Fitting three modes finds weakly favored solution at $M = 1.02 M_\odot$, $M_{\rm acc} = 0.31 \times 10^{-4} M_\odot = 0.23 M_{\rm ign}$

Need more, better characterized modes to constrain rotation

Summary

- Accreting WDs are reheated by “compressional heating” and Hydrogen “simmering”
- Equilibrium T_c allows relation of observables to $M, \langle \dot{M} \rangle$
- Find good agreement between Interrupted Magnetic Braking and observations
  - Quiescent Dwarf Nova $T_{\rm eff}$
  - Reproduces classical nova period distribution
  - Both support a factor of 10 or more drop in $\langle \dot{M} \rangle$ across gap
  - Comparison implies $M_{\rm ej} \approx M_{\rm ign}$
- Predict evolution of broadband colors in quiescence, important for surveys such as SDSS
- Predict late time magnitudes for both CVs and AM CVns
- Seismology can determine M, $M_{\rm acc}$, need better data

Accreting WD Envelope



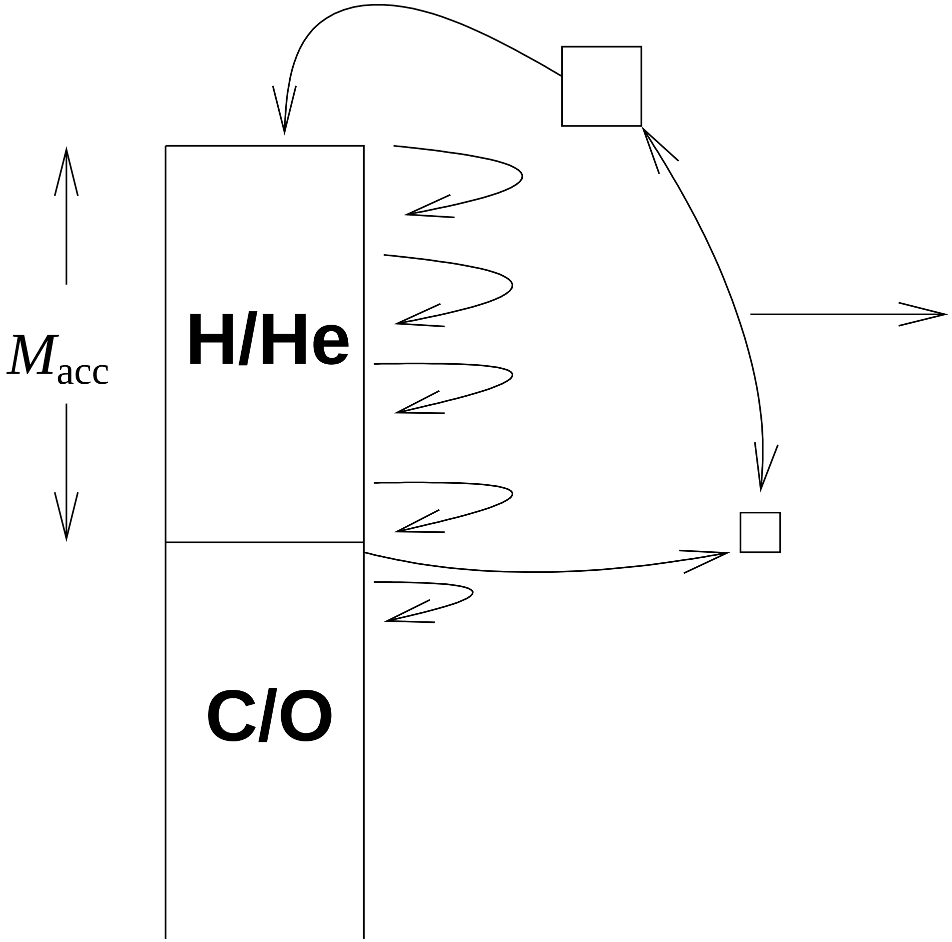
Envelope thermal time

$$\sim 10^3 \text{ yr}$$

Infall energy deposited near surface and quickly radiated away

Interested in energy deposited deep in the envelope

Accreting WD Envelope



quasi-static envelope

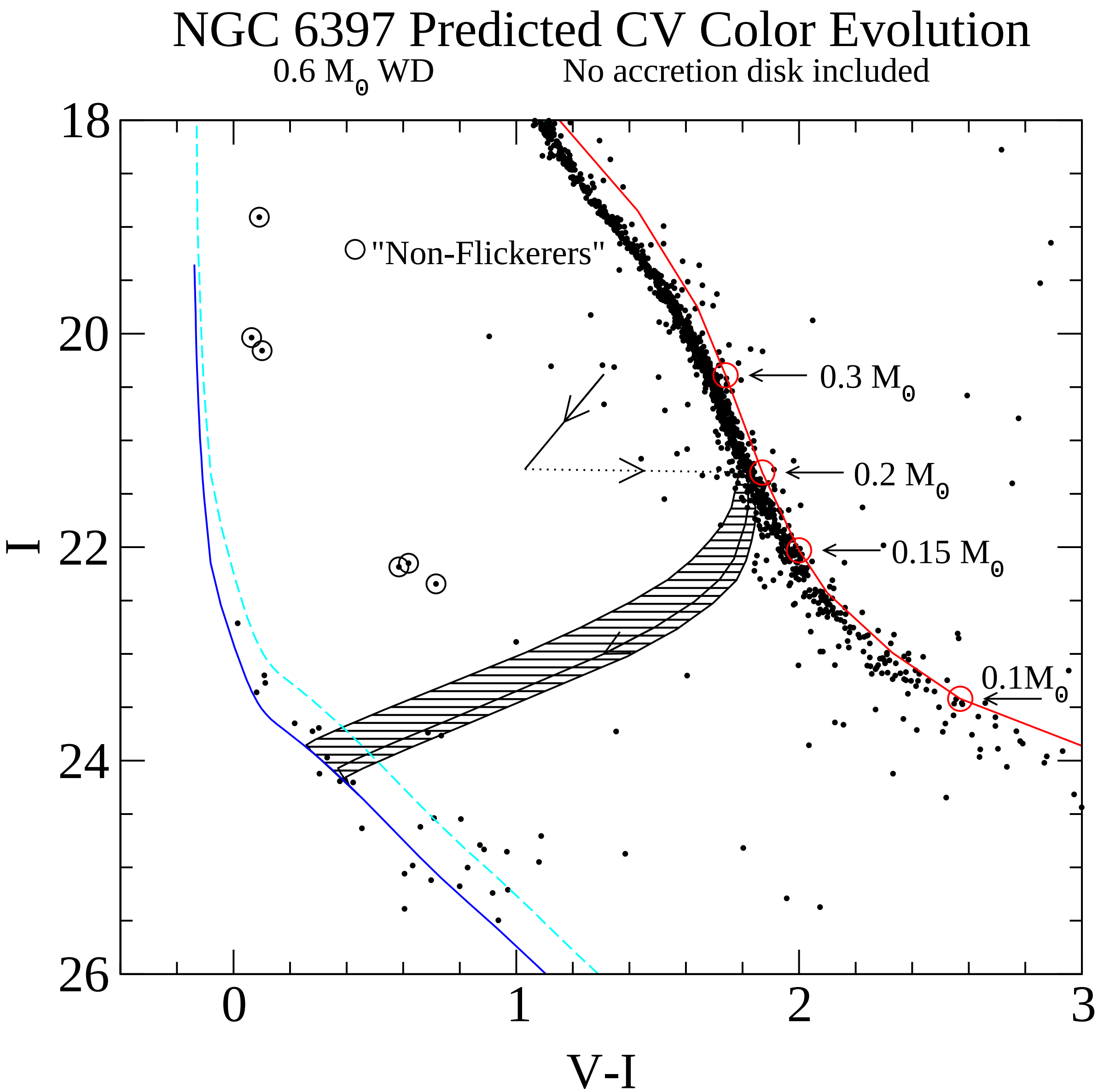
$$L_{\rm env} \sim gh\langle\dot{M}\rangle \sim \langle\dot{M}\rangle\frac{kT_c}{\mu m_p}$$

So actually:

$$\boxed{T_{\rm eff}(M, \langle\dot{M}\rangle, M_{\rm acc}, T_c)}$$

$$\boxed{M_{\rm ign}(M, \langle\dot{M}\rangle, T_c)}$$

NGC 6397



Proper-motion selected members of NGC 6397

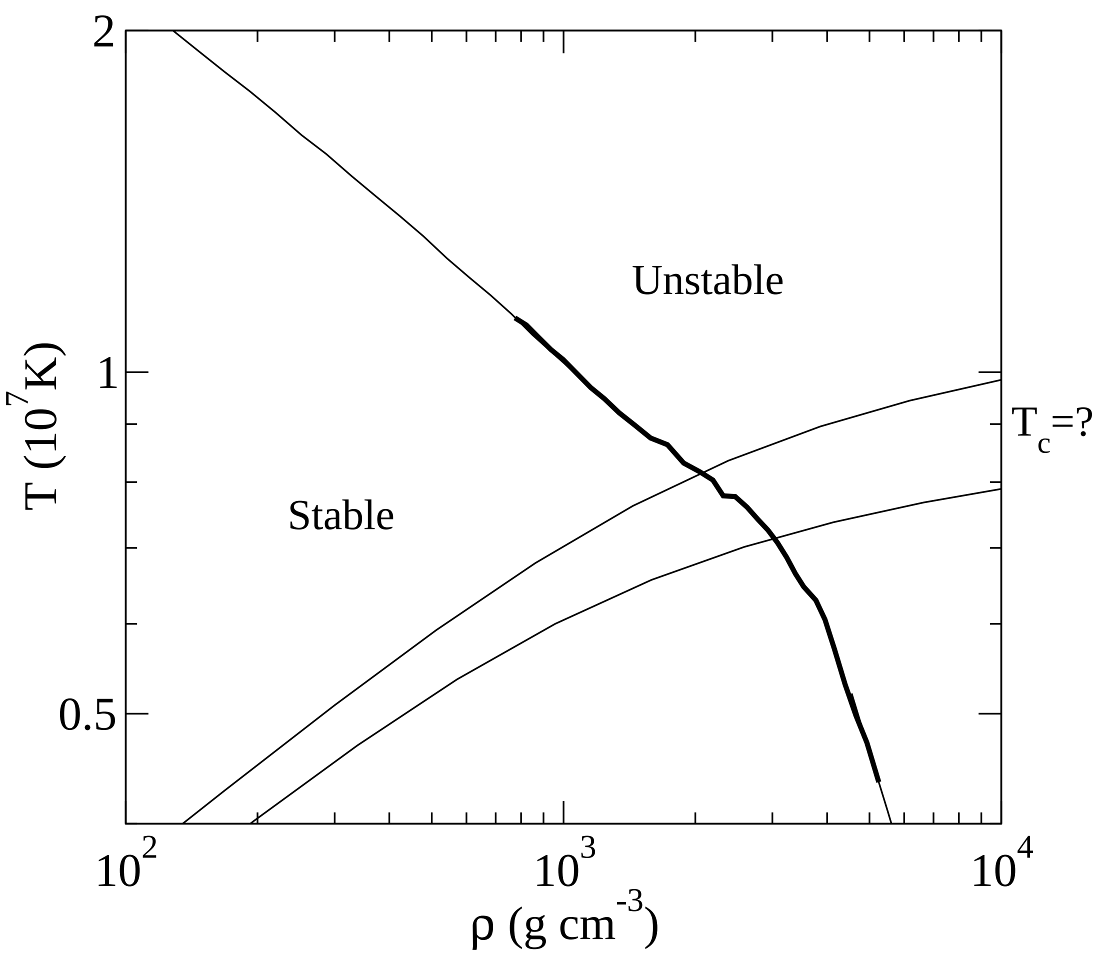
(King, Anderson, Cool, & Piotto 1998, ApJ, 492L, 37)

and Non-Flickerers

(Taylor, Grindlay, Edmonds, & Cool 2001, ApJ, 553L, 169)

T_c and Classical Nova Ignition

Conditions at base of H/He:



Evaluating envelope stability:

$$\frac{\partial \epsilon_N}{\partial T} = \frac{\partial \epsilon_{\rm cool}}{\partial T}$$

What thermal state (T_c) corresponds a given $\langle \dot{M} \rangle$?