Classical Novae and the Thermal History of CV White Dwarfs

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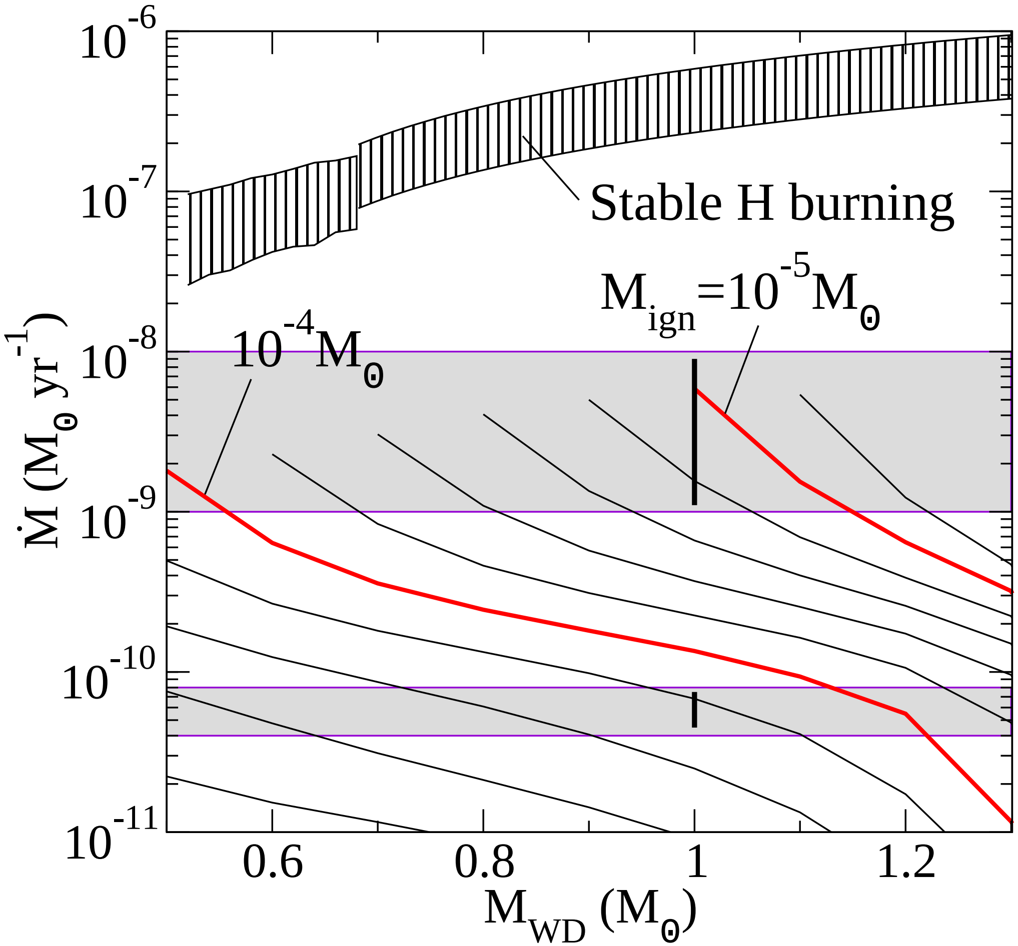
Motivation

- Want to understand how outbursts fit in with the more day-to-day aspects of the accreting systems in which they occur
- Constrain short period binary population: angular momentum loss, mass distributions, period distributions
- Provide context for individual runaways

Outline

- Accreting envelopes and classical nova ignition
  - Thermal Structure of Accreting envelopes
  - thermonuclear instability – $M_{\rm ign}$
  - Equilibrium T_c
- Evolution of T_c in CVs
  - Accretion in CVs – Interrupted Magnetic Braking
  - Evolution of interior thermal state under accretion
  - Period-specific Nova rate

Available Parameter Space



Contours spaced by $\Delta \log(M_{\rm ign}/M_\odot) = 0.2$

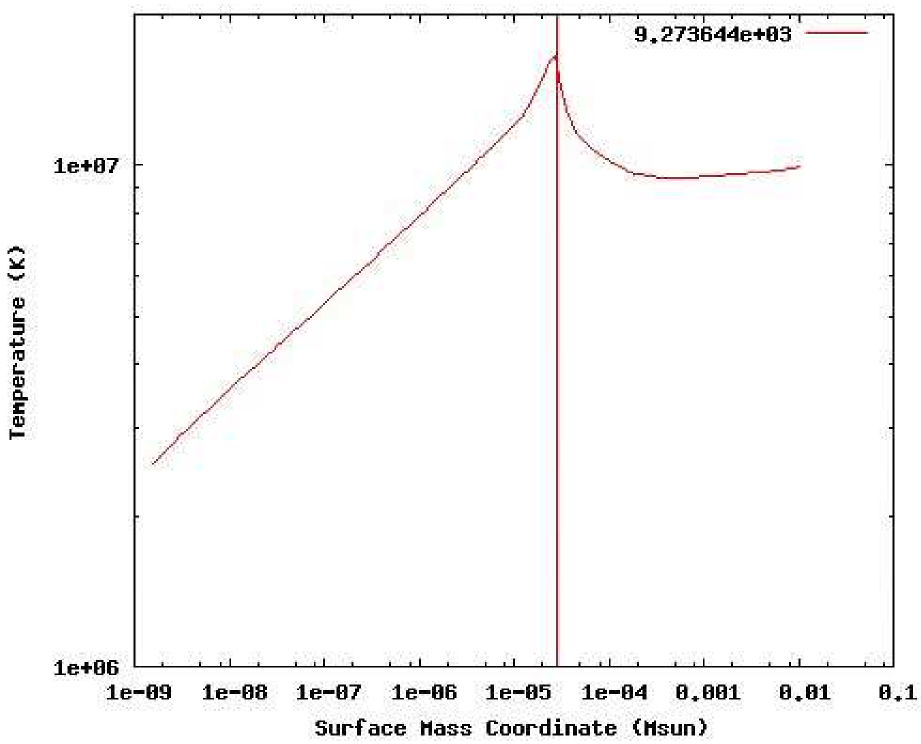
Townsley & Bildsten 2005, ApJ, 628, 395

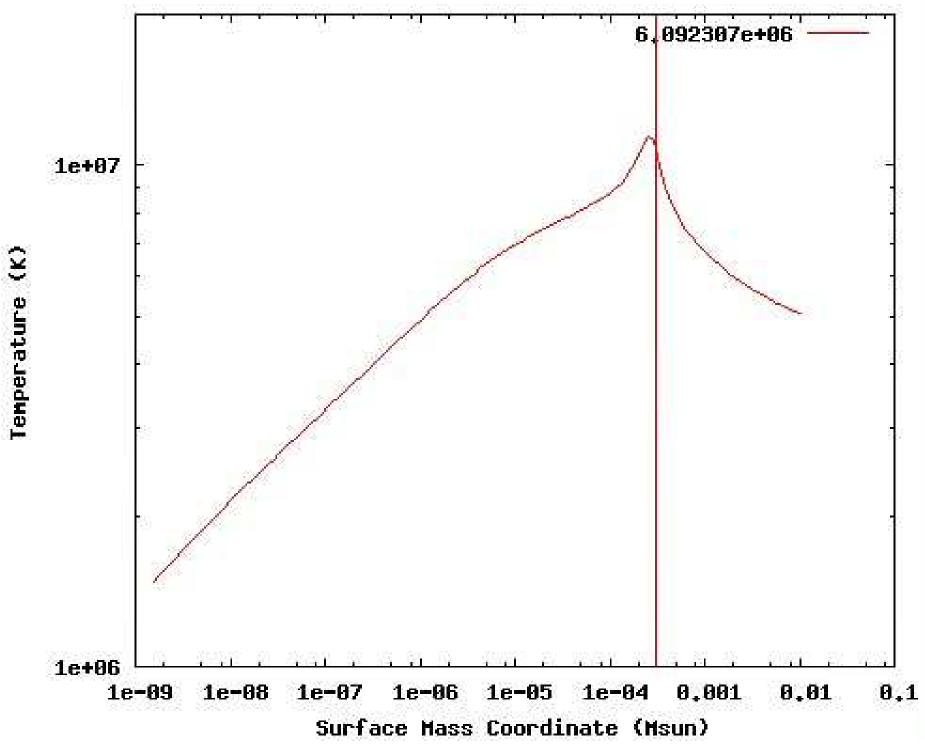
Strong contrast in $M_{\rm ign}$ at around few$\times 10^{-10} M_\odot$ yr^{-1} created by change in ignition mode due to different T_c as determined by $\langle \dot{M} \rangle$ (more on this later).

CVs generally are thought to have accretion rates that are low or high, but not much in between.

A system at a given mass can have a factor of 10 range in $M_{\rm ign}$ depending on what evolutionary stage it is in.

Two Kinds of Ignition





m

$$\langle \dot{M} \rangle = 3 \times 10^{-9} M_\odot \ \mathrm{yr}^{-1}$$

$$T_c = 10^7$$

Direct to $p + \mathrm{C}$ or $^3\mathrm{He} + ^3\mathrm{He}$

Most novae by number

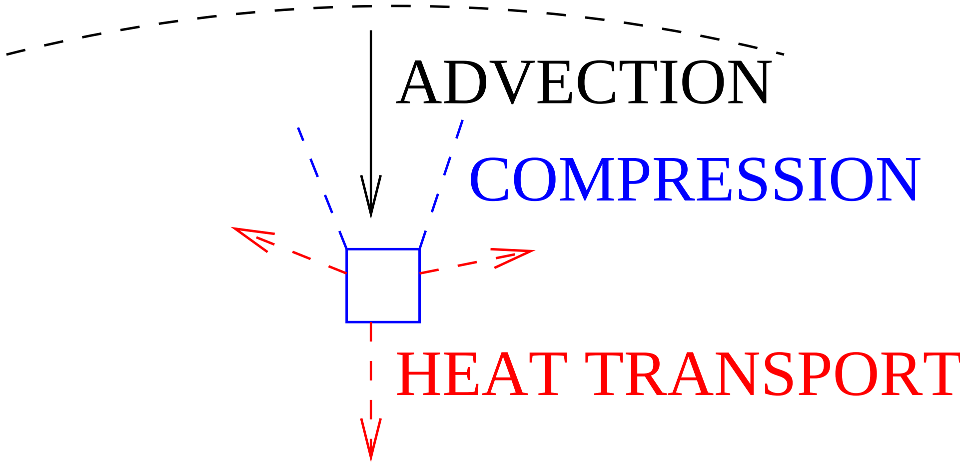
$$\langle \dot{M} \rangle = 5 \times 10^{-11} M_\odot \ \mathrm{yr}^{-1}$$

$$T_c = 5 \times 10^7$$

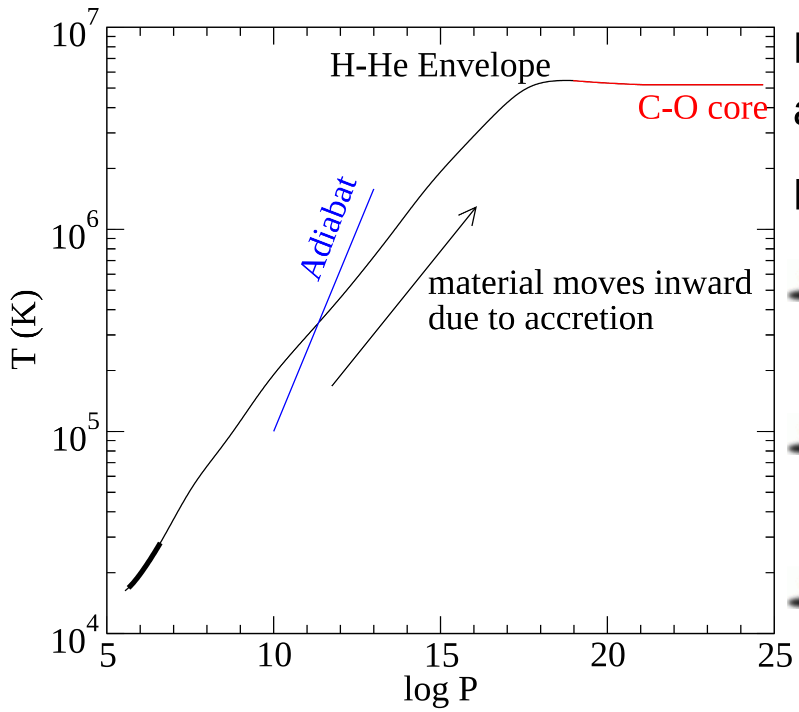
$p + p$ (partial chain) envelope heating eventually leads to $p + \mathrm{C}$

Large accumulated mass

Heat Sources



(very) leaky entropy advection

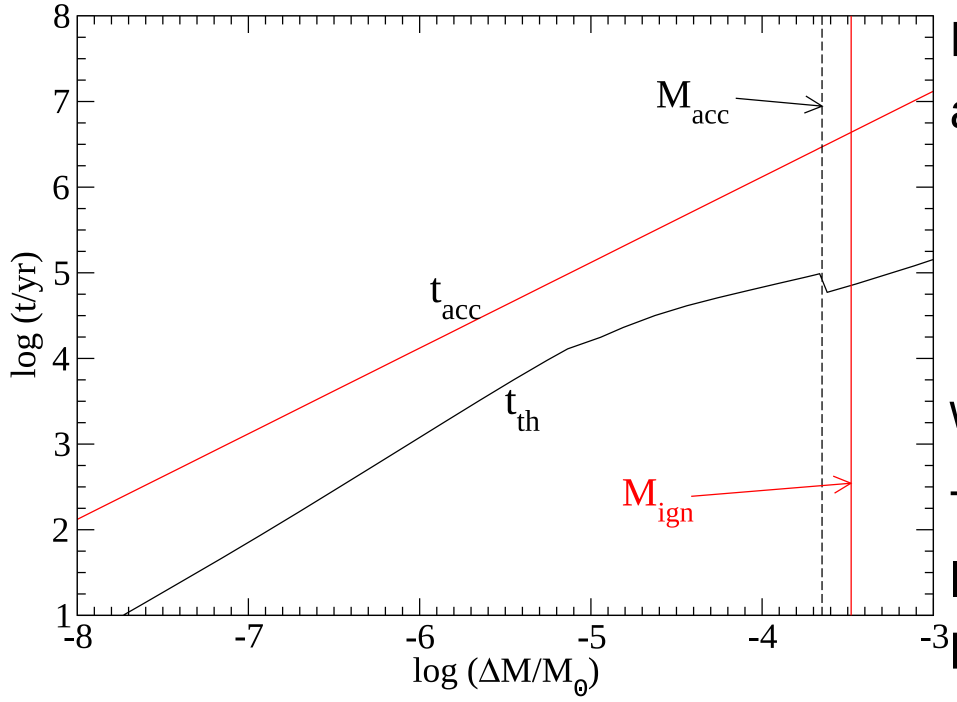


Heat liberated by compression is transferred out to surface and in to core. Often called “compressional heating”.

Heat sources:

- Accretion light: only very near surface while actively accreting
- Compression: throughout star, mostly in light-element layer (really gravitational potential energy)
- Nuclear “simmering”: fusion near base of accreted layer (eventually becomes fast and triggers classical nova)
- Core heat capacity

Quasi-static Profile



Local thermal time short compared to accretion

$$t_{\rm th} \equiv \frac{c_P T}{\left(\frac{4acT^4}{3\kappa y^2}\right)} \quad < \quad t_{\rm acc} \equiv \frac{\Delta M}{\langle \dot{M} \rangle}$$

where $y = \Delta M / 4\pi R^2$ is the column depth.

Thermal state set by flux from deeper layers rather than from fluid element's history.

Heat equation near surface:

0 static

$$-\frac{dL}{dM_r} + \epsilon_N = T\left(\frac{\partial}{\partial t} + v_r \frac{\partial}{\partial r}\right) s = T\frac{\partial s}{\partial t} + T v_r \frac{\partial s}{\partial r}$$

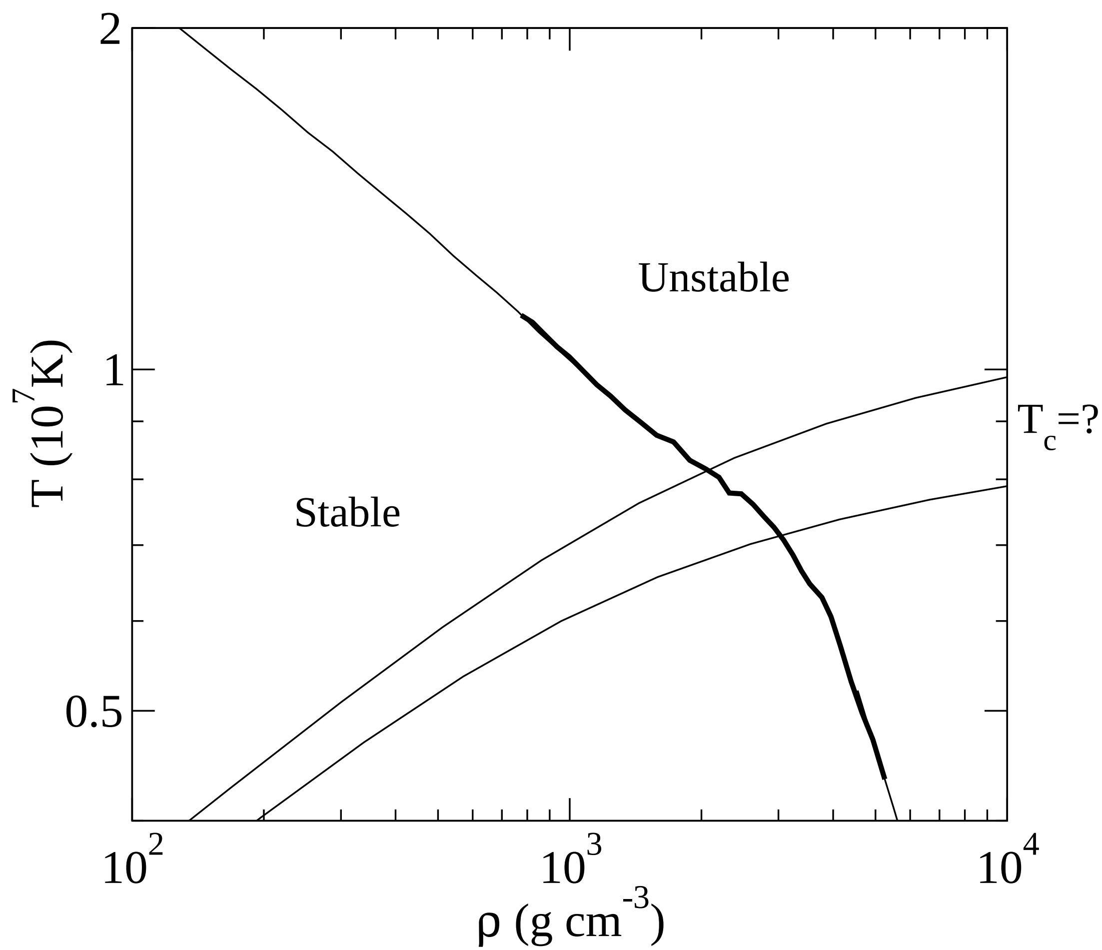
where $v_r = -\langle \dot{M} \rangle / 4\pi r^2 \rho$. Solve with structure equations. Gives excellent representation of envelope sructure.

$$L \simeq \frac{kT_c}{\mu m_p} \langle \dot{M} \rangle$$

Energy release related to heat content of compressed material.

T_c and Classical Nova Ignition

Physical Conditions at base of H/He Envelope determine runaway

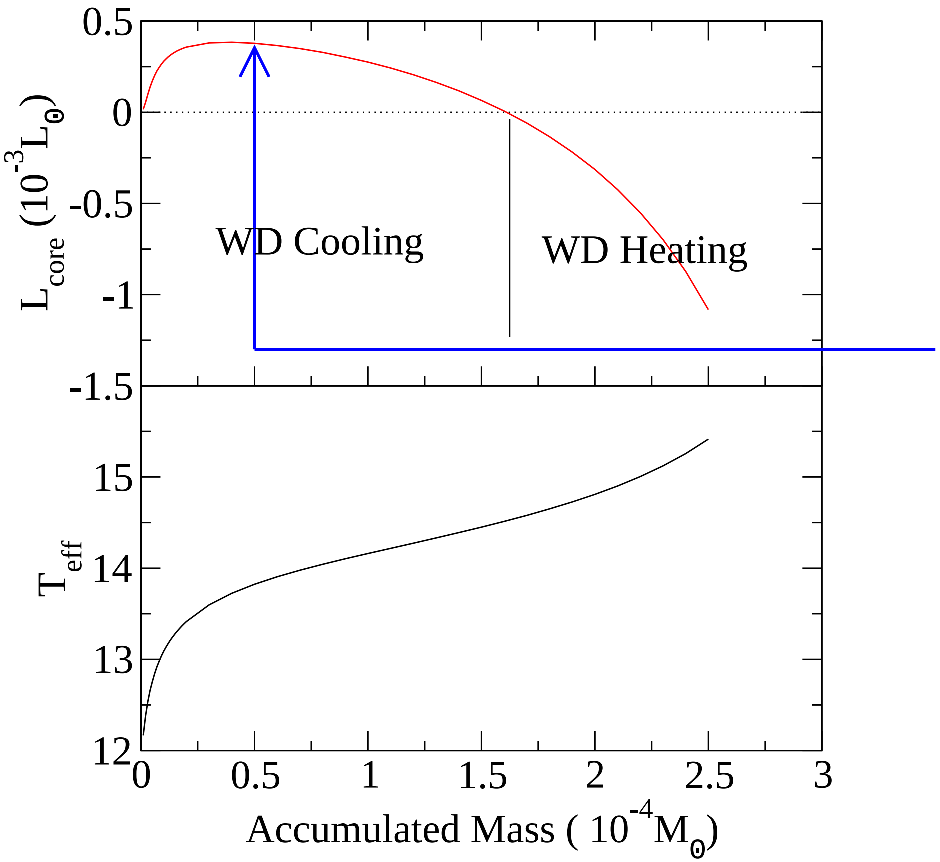


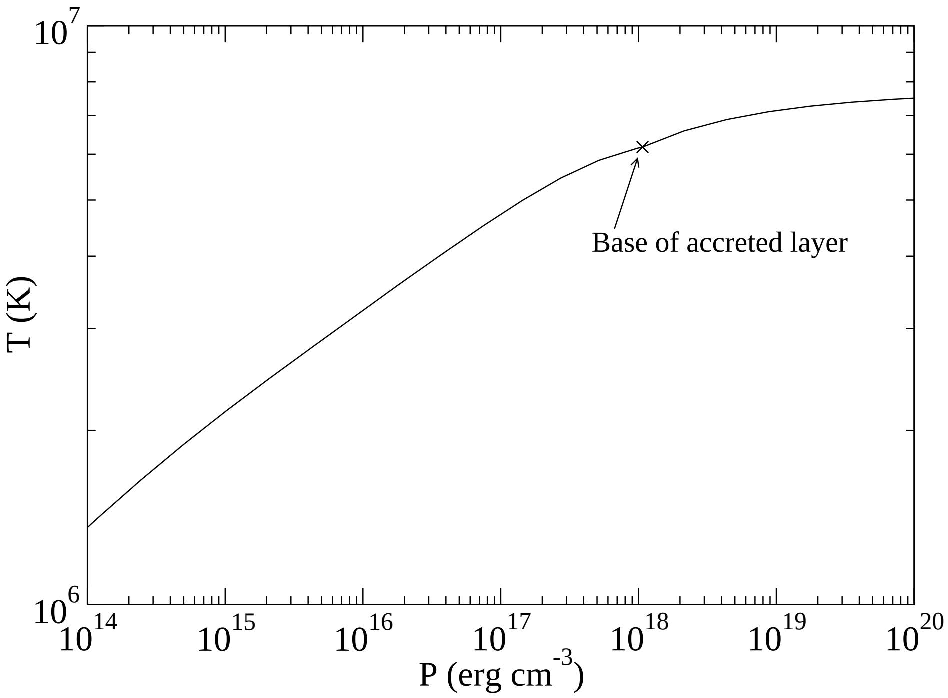
Evaluating envelope stability:

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

- One-zone approximation, $\epsilon_{\rm cool} \propto 4acT^4/\kappa y^2$, only works in upport portion.
- Lower part of curved better modeled by $\epsilon_{\rm cool} = L(T_c)/M_{\rm acc}$, were $L(T_c)$ is given by that of a cooling WD: radiative envelope overlying a conductive region.
- Thermal state (T_c) has an important influence on when the instability line is crossed.
- Composition has significant influence on position of upper portion.

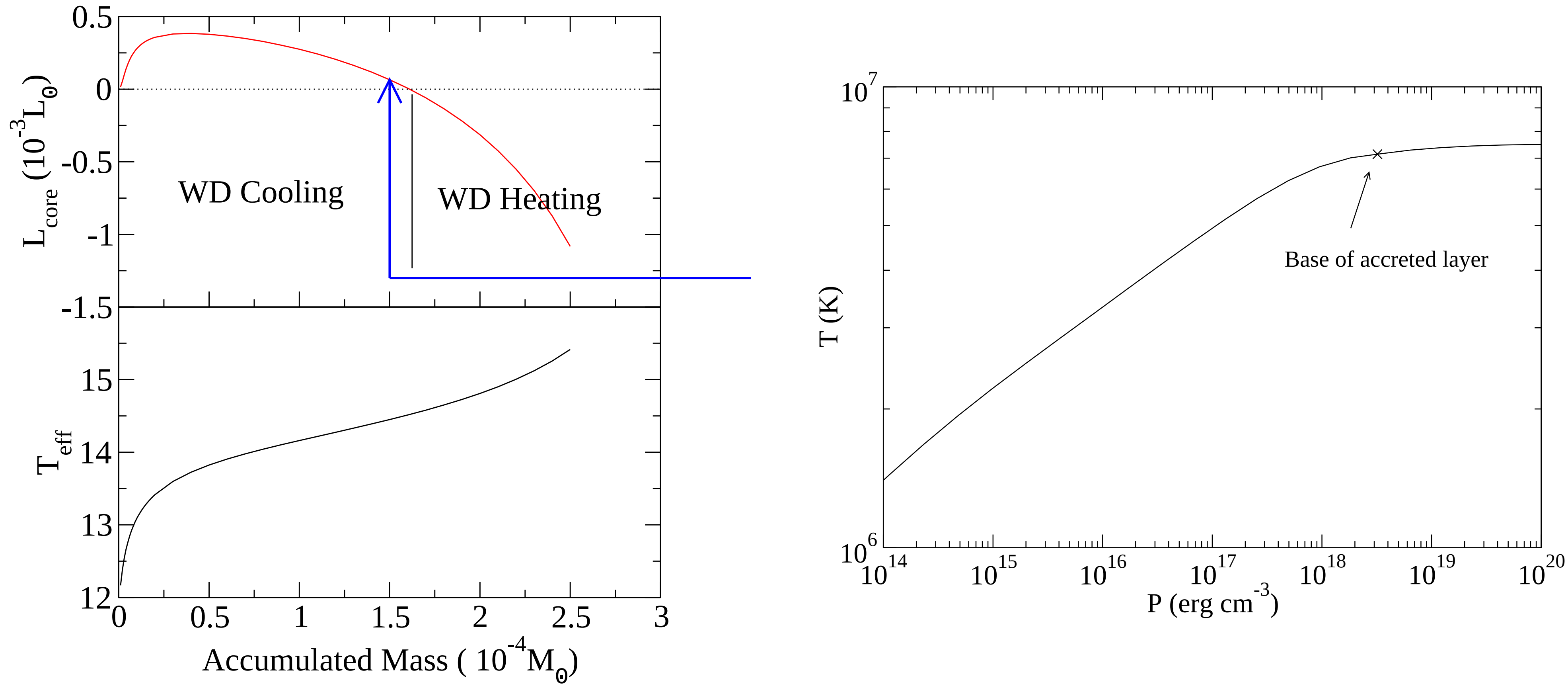
Cooling-Heating Cycle





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

Cooling-Heating Cycle



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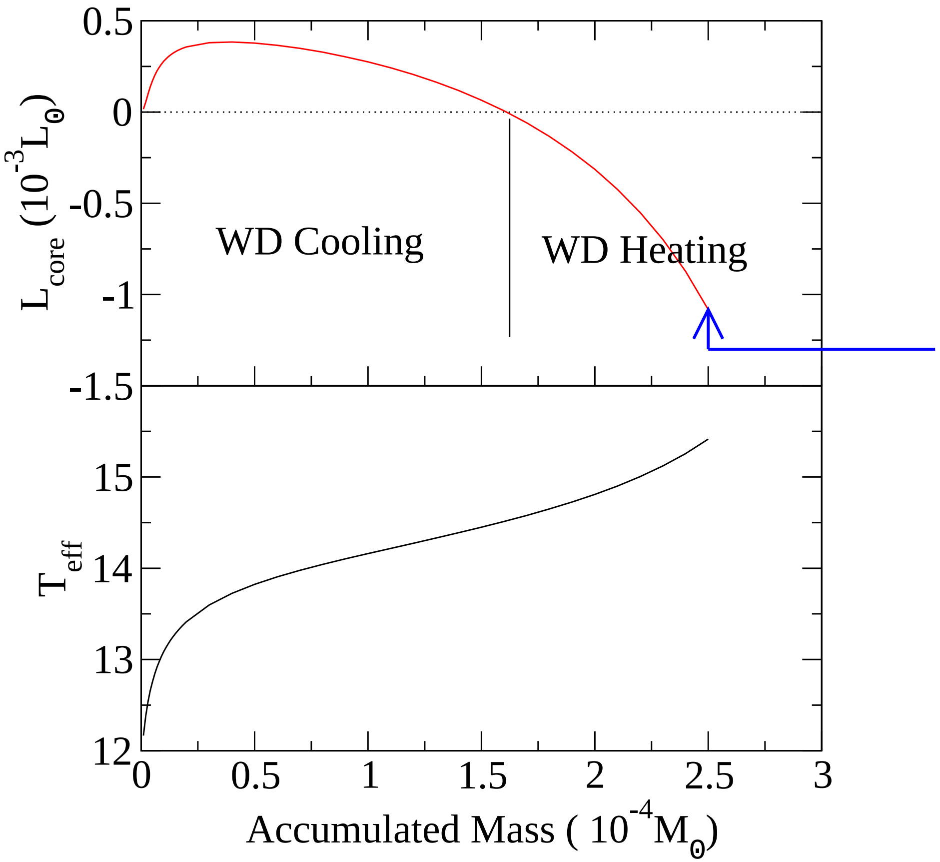

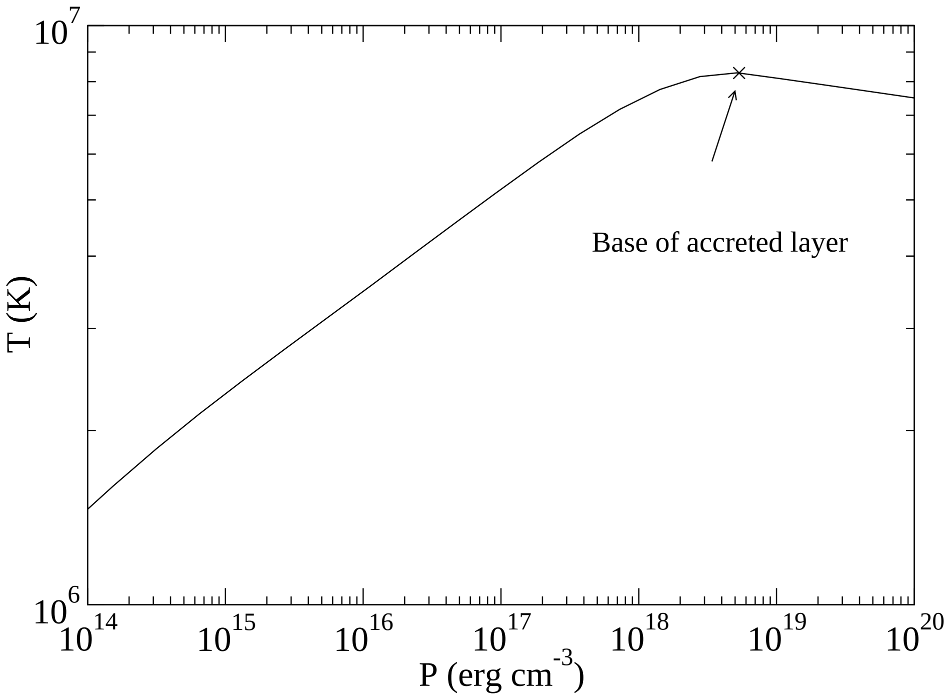

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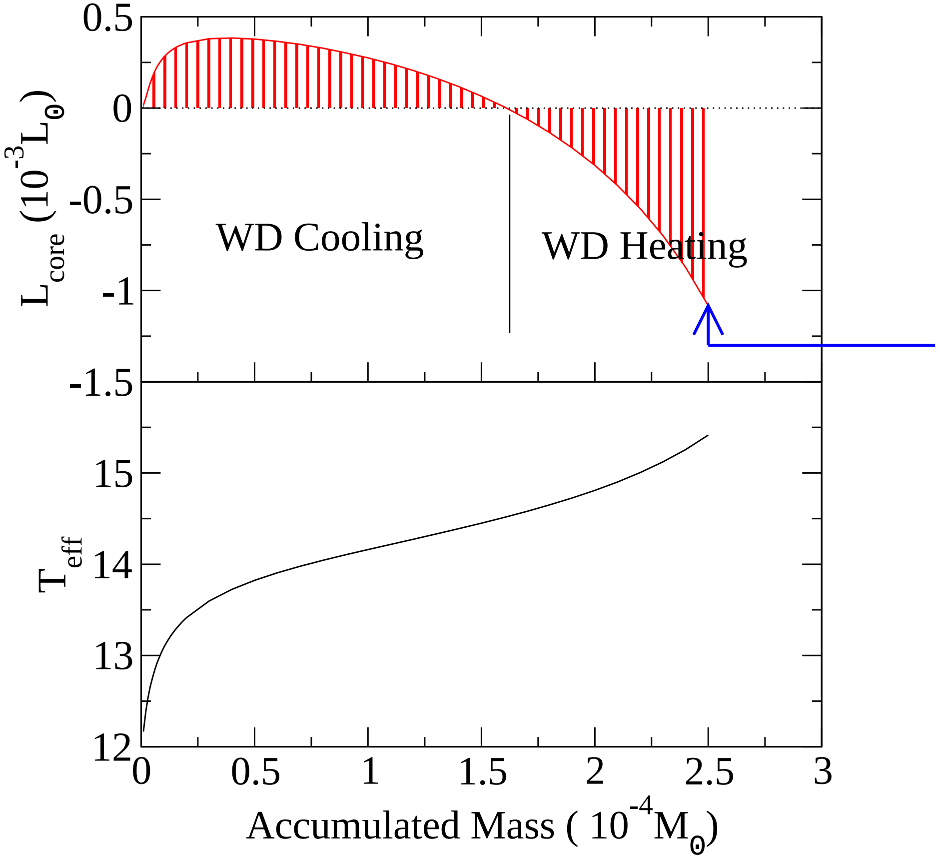
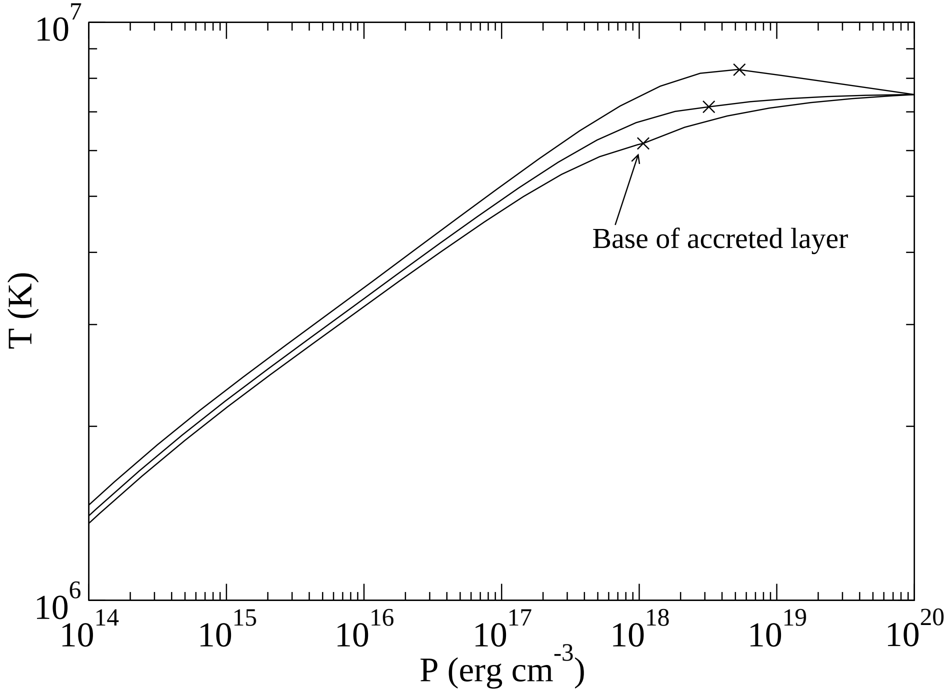




- Core will be Reheated until equilibrium is reached.
  Core thermal time $\sim 10^8$ yr

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

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

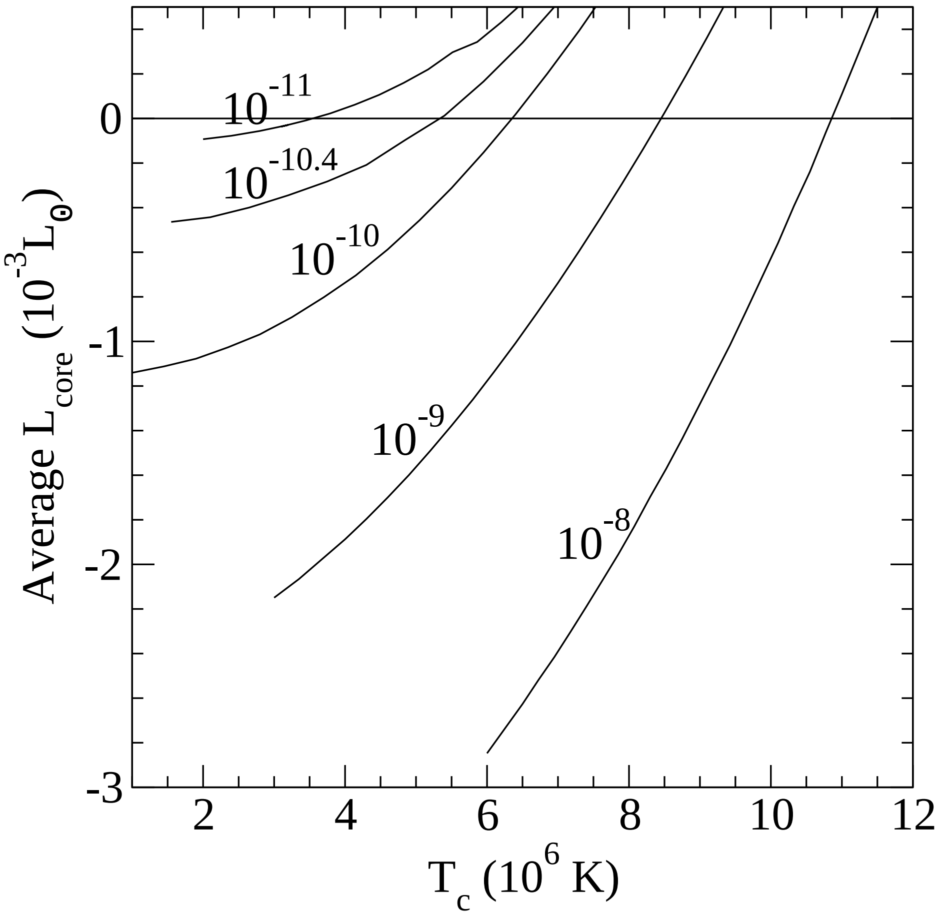
$$\langle L_{\rm core}\rangle = \frac{1}{t_{\rm CN}}\int_0^{t_{\rm CN}} L_{\rm core}\, dt$$

When $M_{\rm ej} = M_{\rm ign}$, $\langle L_{\rm core}\rangle = 0$ defines an Equilibrium $T_{\rm core}$ which is set by M and $\langle \dot{M}\rangle$

Can approximate evolution:

$$\langle L_{\rm core}\rangle(T_c, \dot{M}) = C_{WD}\,\frac{dT_c}{dt}$$

where C_{WD} is the total heat capacity of the WD – proportional to mass (have to be careful with latent heat at crystallization)

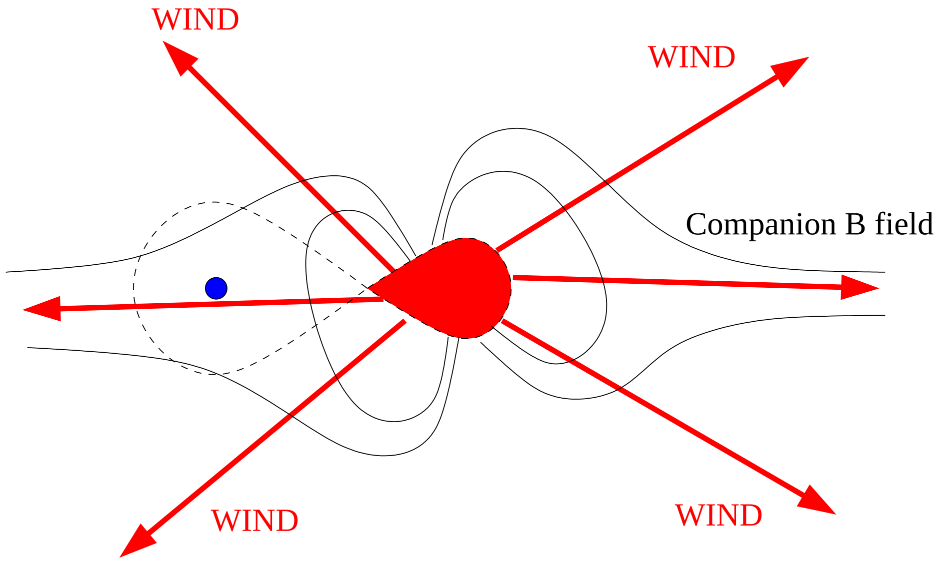


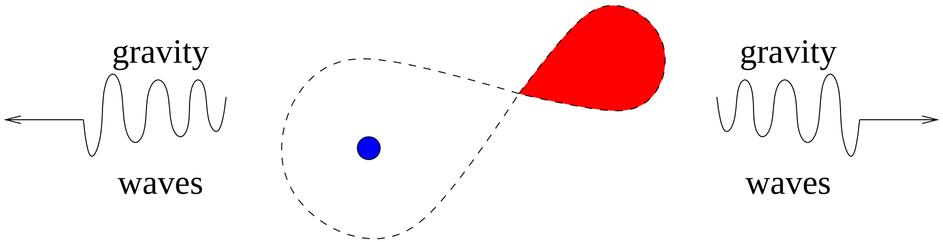
Cataclysmic Variable Evolution

$\dot{M}(t)$ history

CV Angular Momentum Loss

$\dot{J}$ determines evolution of compact binary





Magnetic Braking

high $\dot{J}$, $P_{\rm orb} \gtrsim 3$ hours

Magnetically attached wind from companion star

$$\dot{J}_{\rm mb} = -9.4 \times 10^{38}\,{\rm erg} \left(\frac{M_2}{M_\odot}\right)\left(\frac{R_2}{R_\odot}\right)^3\left(\frac{P_{\rm orb}}{\rm hr}\right)^{-3}$$

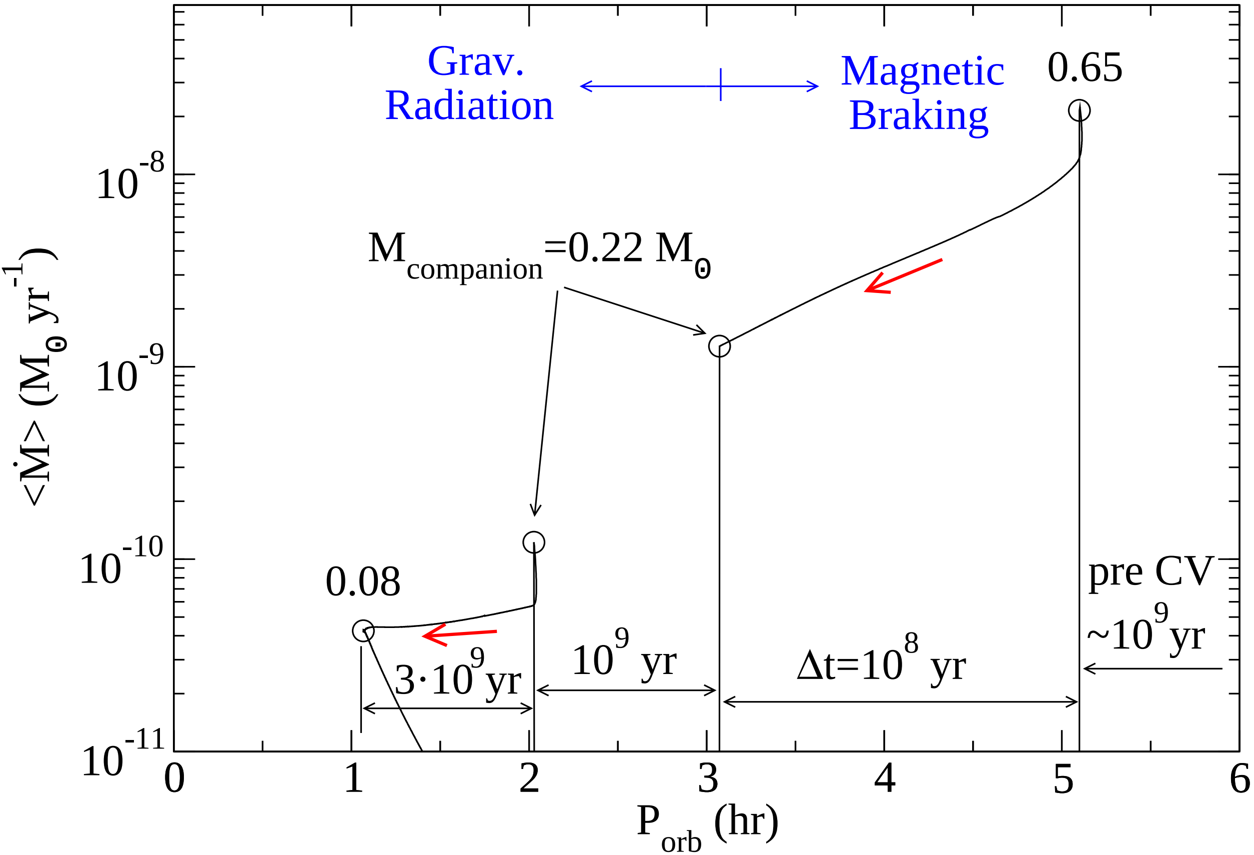
Gravitational Radiation

low $\dot{J}$

$$\dot{J}_{\rm gr} = -\frac{32 G Q^2 \omega^5}{5c^5}$$

$$= -2.7 \times 10^{37}\,{\rm erg}\left(\frac{a}{R_\odot}\right)^4\left(\frac{M_{\rm WD} M_2}{M_t M_\odot}\right)^2\left(\frac{P_{\rm orb}}{\rm hr}\right)^{-5}$$

Interrupted Magnetic (Wind) Braking?



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

Systems evolve from long to short orbital periods due to angular momentum losses causing the orbit to decay.

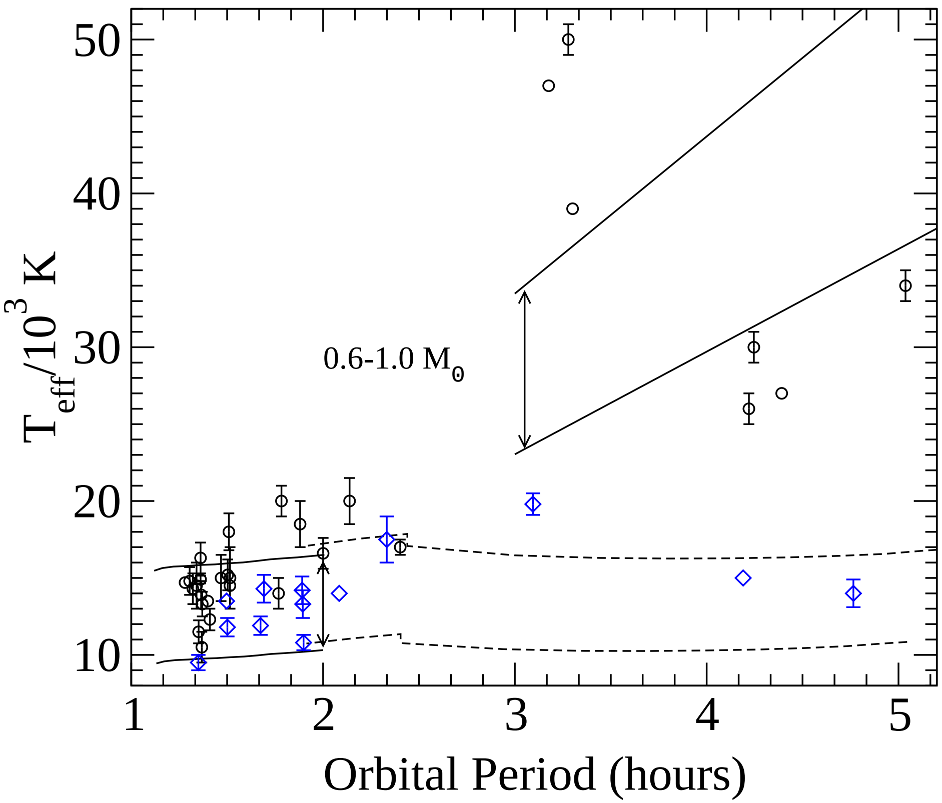
Period gap caused by sudden drop in angular momentum loss rate.

- Evolved from prescriptions which reproduced the companion contraction necessary for the period gap.
- Predicts a strong contrast in both $\langle\dot{M}\rangle$ and evolution time – and therefore space density – of period bins
- Difficult to test due to CV variability and complexity of disks, but progress can be made by other means such as WD $T_{\rm eff}$. (Townsley & Bildsten 2003, ApJ, 596, L227)

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

Townsley & Bildsten 2003, ApJ, 596, L227

Townsley & Gänsicke, in preparation



○ Low disk state systems (DN, SW Sex)

◇ Magnetics

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

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

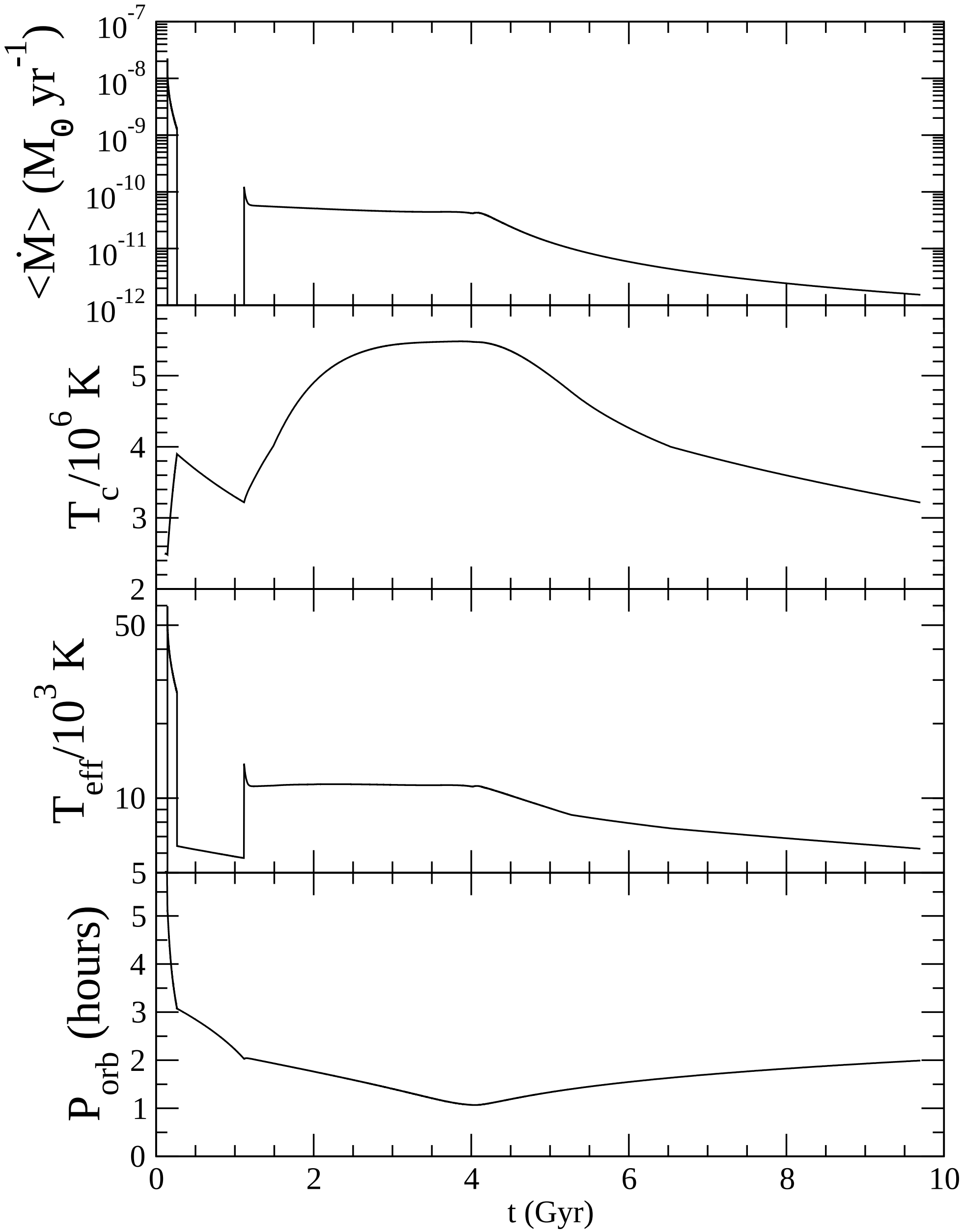
Current Mag. Braking prescription matches well with DN at 4-5 hours

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)

WD Thermal State Evolution



Phases of accretion

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

Phases of WD evolution

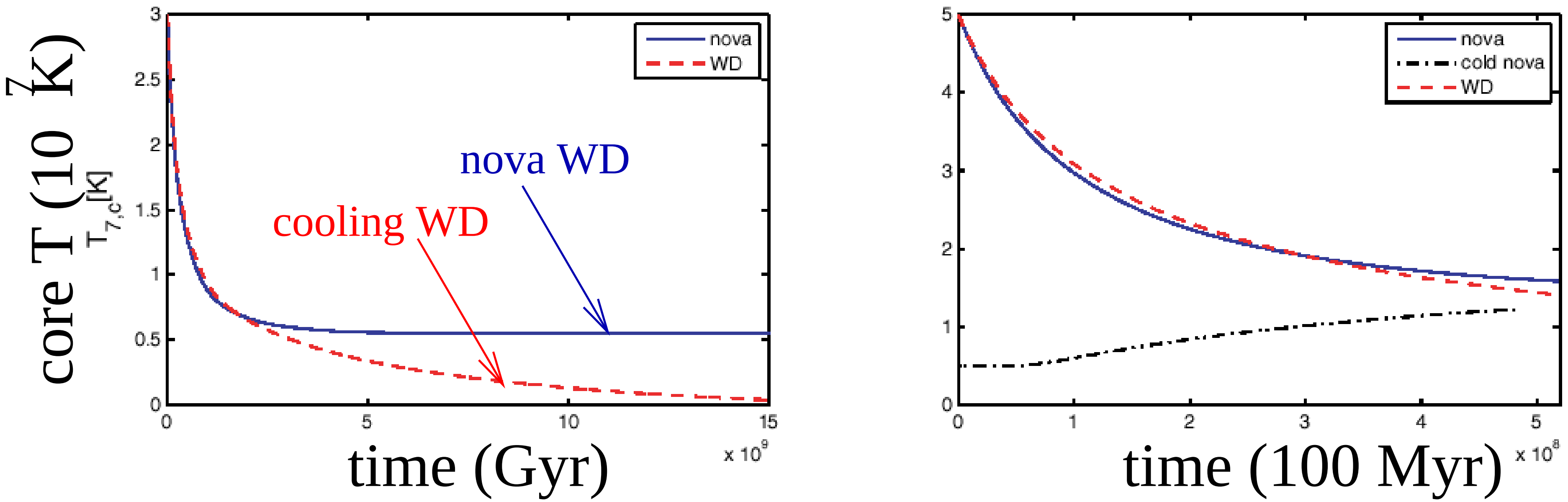
1. Reheating – T_{eff} set by $\langle \dot{M} \rangle$
2. Equilibrium – T_{eff} set by $\langle \dot{M} \rangle$
3. Cooling – T_{eff} set by core cooling

Accretion resets the clock for WD cooling

Classical Nova $P_{\rm orb}$ Distribution

Epelstain, Yaron, Kovetz, Prialnik 2007, MNRAS, 374, 1449
Full, multi-cycle nova simulations

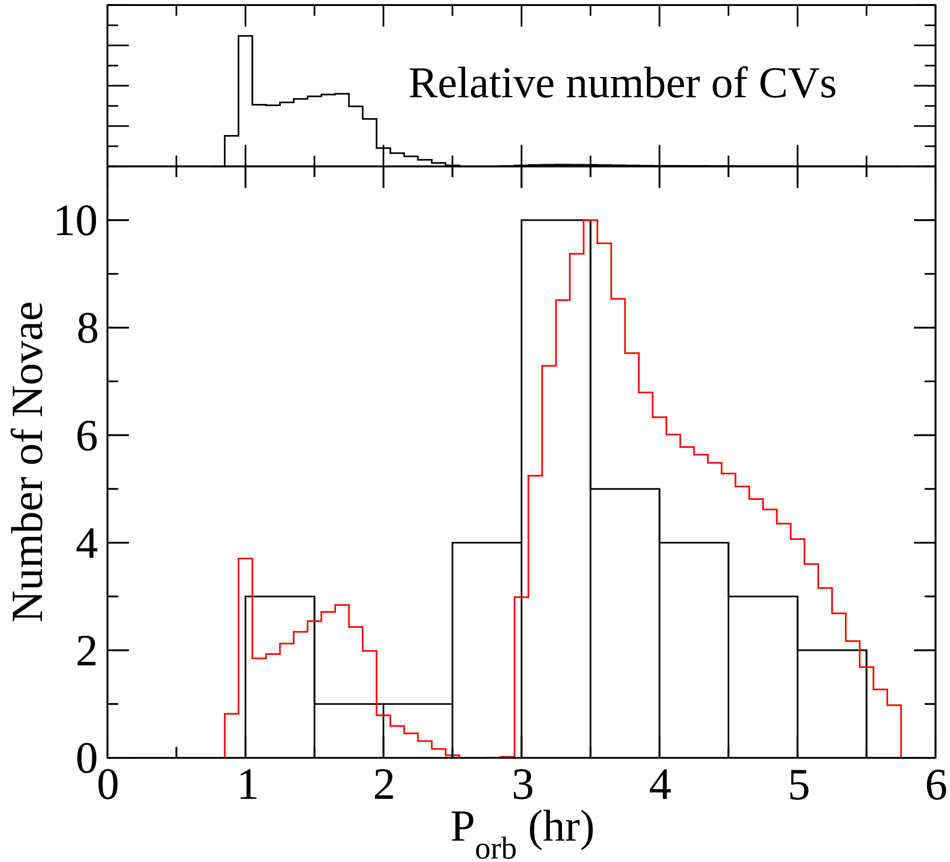
$M = 1.0 M_\odot$, $\langle \dot{M} \rangle = 10^{-11} M_\odot$/yr $\qquad$ $M = 0.65 M_\odot$, $\langle \dot{M} \rangle = 10^{-9} M_\odot$/yr



Demonstrates equilibrium and evolution times. Unlikely to come fully into equilibrium above gap, but plenty of time below gap, especially with the “boost” from above-gap evolution.

Also demonstrates that nova WDs in CVs generally will not stay very hot ($\gtrsim 2 \times 10^7$) for more than a few 100 Myr. (Note being "caught" in this state would be exceedingly rare in any case due to post-CE cooling.)

Classical Nova $P_{\rm orb}$ Distribution



(Townsley & Bildsten 2005, ApJ, 628, 395)

Theory curve uses Interrupted Magnetic Braking for $P_{\rm orb}(\langle\dot{M}\rangle)$ and population n_P

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

$$\nu_{CNP} = n_P \frac{\langle\dot{M}\rangle}{M_{\rm ign}}$$

But since $n_P \propto M_2/\langle\dot{M}\rangle$ this gives

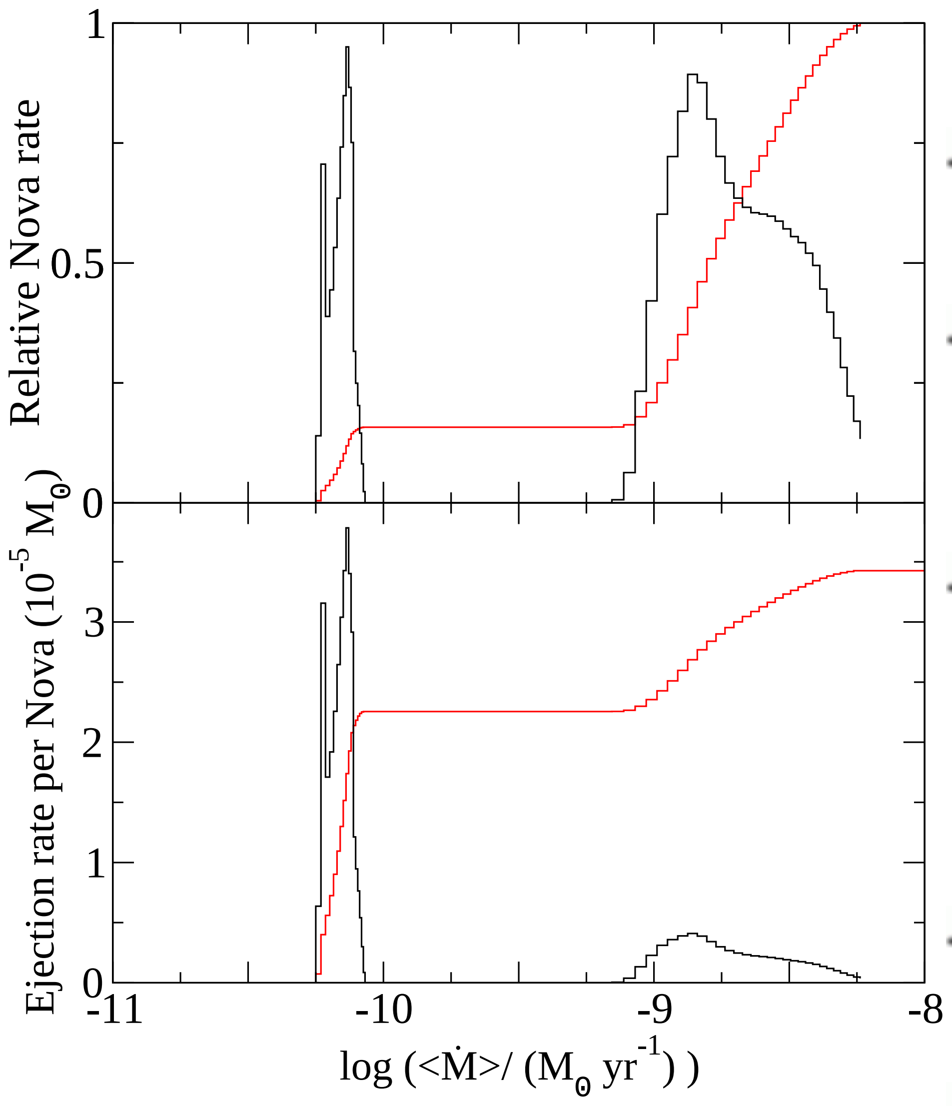
$$\nu_{CNP} \propto \frac{1}{M_{\rm ign}}$$

Thus the *dominant* contribution is from the variation in the ignition mass across the period gap (2-3 hours)

- 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

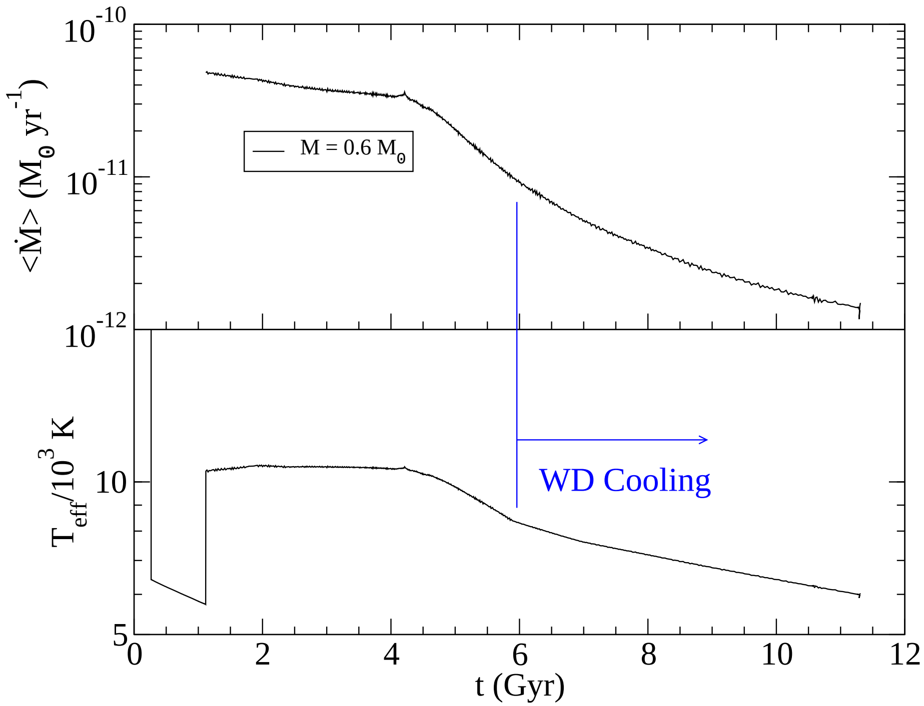
Classical Nova $\langle \dot{M} \rangle$ Distribution

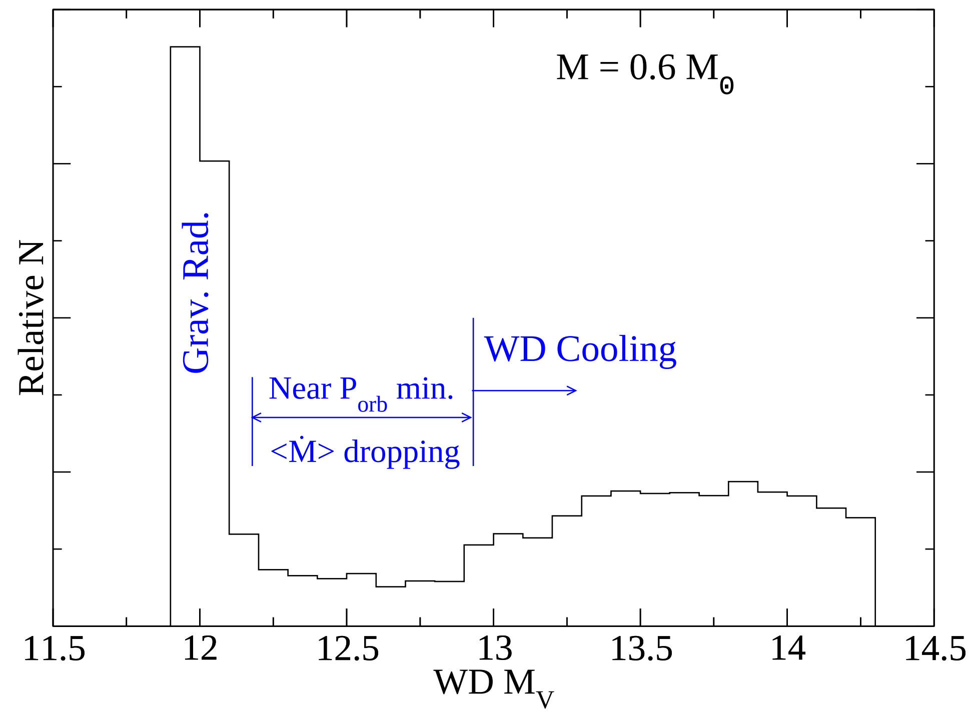
$\Phi(\langle \dot{M} \rangle)$



- Most observed Novae have "high" $\langle \dot{M} \rangle \sim 10^{-9} M_\odot$ yr^{-1}
- Similar amount of matter is ejected from Novae with $\langle \dot{M} \rangle \sim 10^{-9} M_\odot$ yr^{-1} and $\sim 10^{-10} M_\odot$ yr^{-1}.
- Character of ignition very different for these two
  - direct Carbon or ^{3}He trigger
  - p-p heated deep envelope trigger
- Features of Novae which depend on $\langle \dot{M} \rangle$ are expected to have a bimodal character.
- The $P_{\rm orb}$ distribution below 6 hours shows initial indications of this.

Luminosity Function of Old CVs





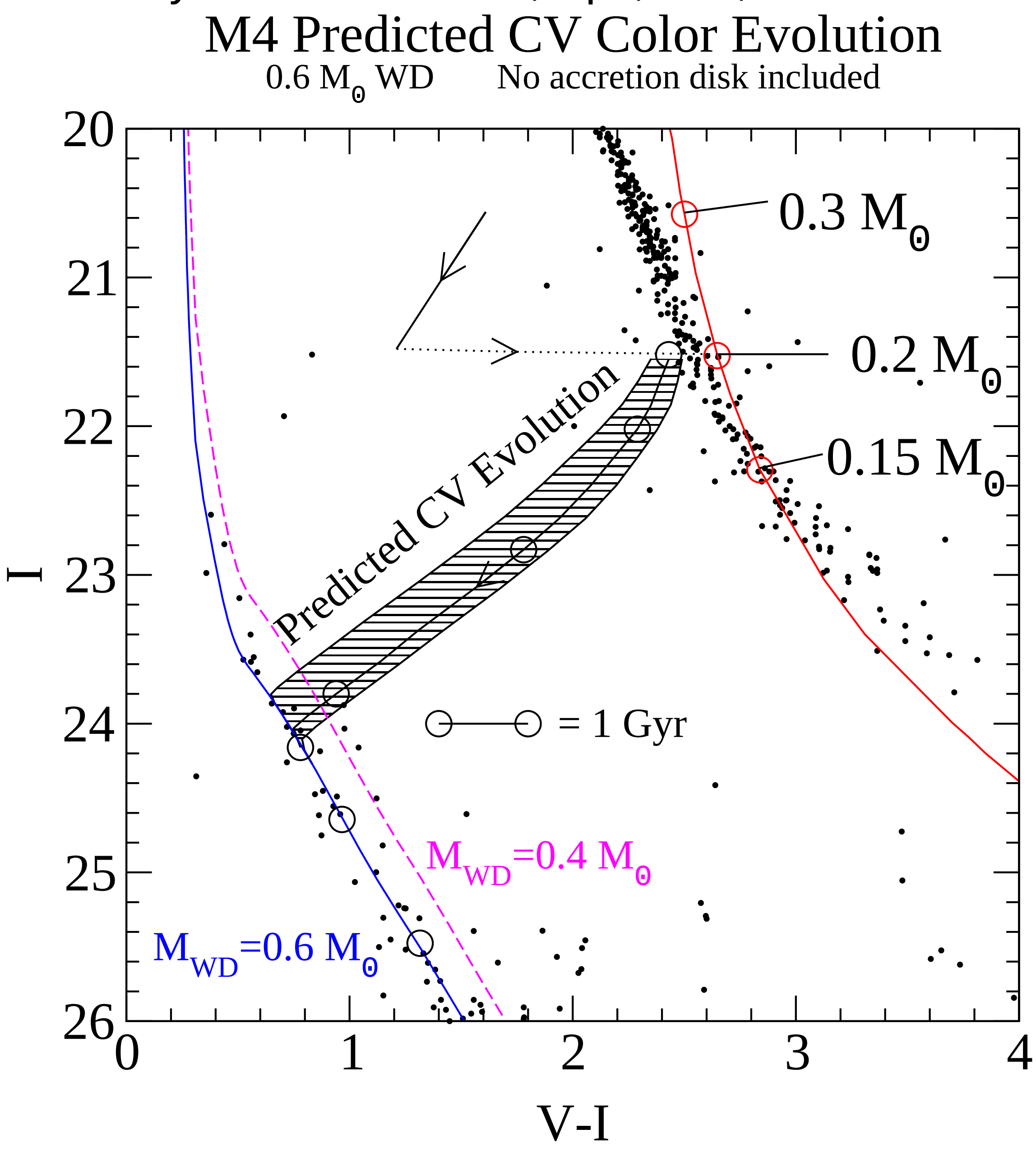
Low $\langle \dot{M} \rangle$ leads to infrequent disk outbursts

CV V magnitude dominated by WD

Most old CVs appear as cooling WDs until inspected carefully

Broadband CV Spectral Evolution

Townsley & Bildsten 2002, ApJ, 565, L35



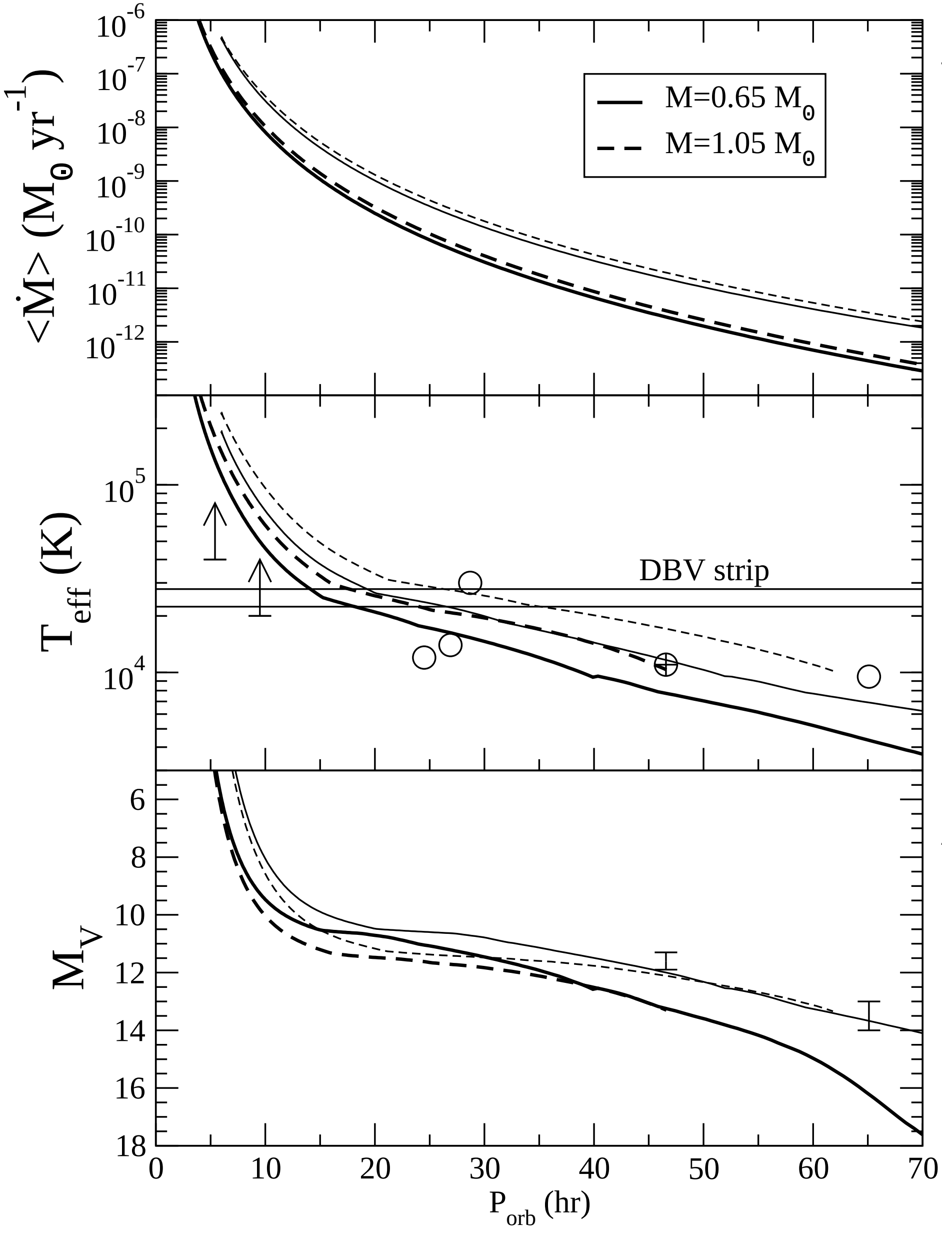
Proper-motion selected members of M4 at 4 core radii (Richer et al. 2002, ApJ, 574L, 151)

Color selection criteria for old CVs

CVs Mixed with WD population used to date cluster

Evolution of He Accretors (AM CVns)

Bildsten, Townsley, Deloye, & Nelemans 2006, ApJ, 640, 466



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)

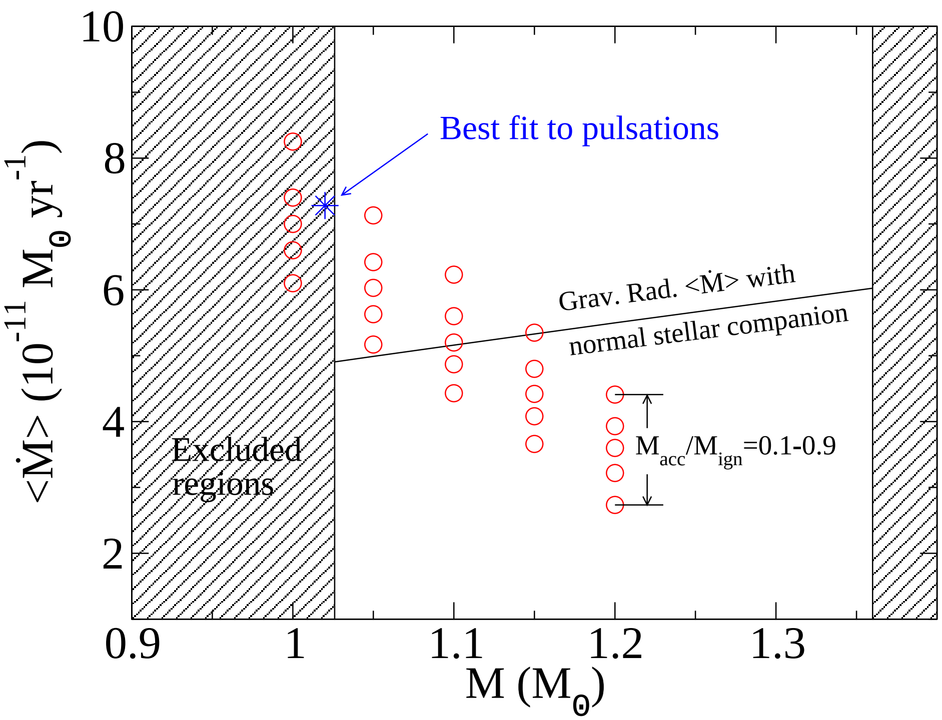
Similar evolution: reheating, equilibrium (short!), WD cooling

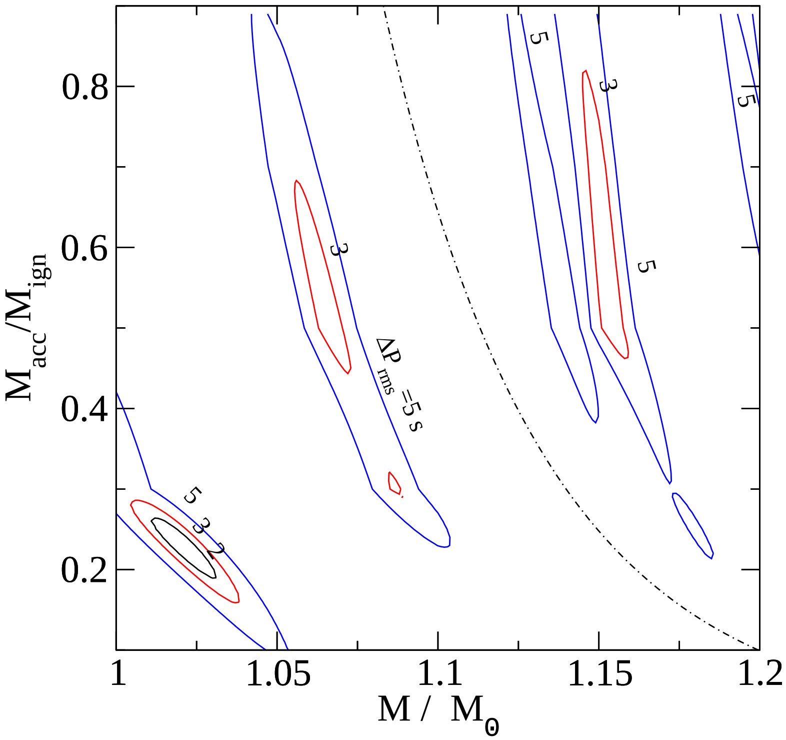
Accretion disk phenomenology not well understood, two-state (DN) accretion expected with increasing time spent in quiescence

Both measured M_V agree well with theory!

Accreting WD Seismology

Townsley, Arras, Bildsten 2004, ApJ, 608, L105





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

Only three modes observed, not well characterized. Fitting these with non-rotating finds weakly favored solution at $M = 1.02 M_\odot$, $M_{\rm acc} = 0.31 \times 10^{-4} M_\odot = 0.23 M_{\rm ign}$

But rotation can greadly modify mode spectrum:
Stay for talk by Boris Gänsicke on HS2331 this afternoon.

Wide variety of driving conditions: Intermediate (between DA and DB) instability strip for modestly enhanced He in donor. (see Arras, Townsley, & Bildsten 2006, ApJ, 643, L119)

Summary

- Accreting WDs are reheated by “compressional heating” and Hydrogen “simmering”
- Equilibrium $T_{\rm core}$ allows relation of observables to $M, \langle \dot{M} \rangle$
- Consistent with quiescent $T_{\rm eff}$, indicating variation in $\langle \dot{M} \rangle$ across period gap
- Reproduces classical nova $P_{\rm orb}$ distribution
- Evolution of broadband colors in quiescence
- Late time magnitudes and $T_{\rm eff}$ for both CVs and Helium accretors
- Seismology can determine spin, M, $M_{\rm acc}$