Hydrogen Ignitions in Cataclysmic Variables

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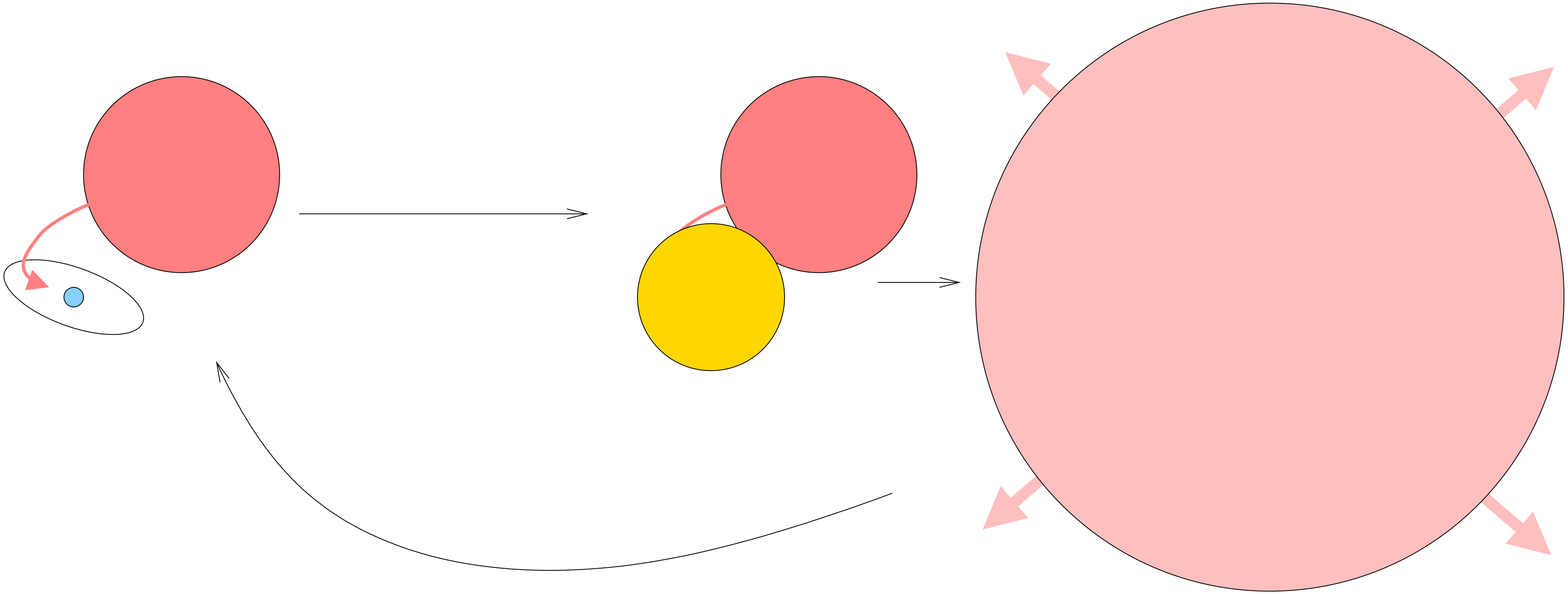
Motivation

- 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

- Thermal Structure of Accreting envelopes
- thermonuclear instability – $M_{\rm ign}$
- Equilibrium T_c
- Accretion in Catalysmic Variables – expected$\langle\dot{M}\rangle$
- Period-specific Nova rate
- Open questions

Nova Accretion and Outburst



Accretion

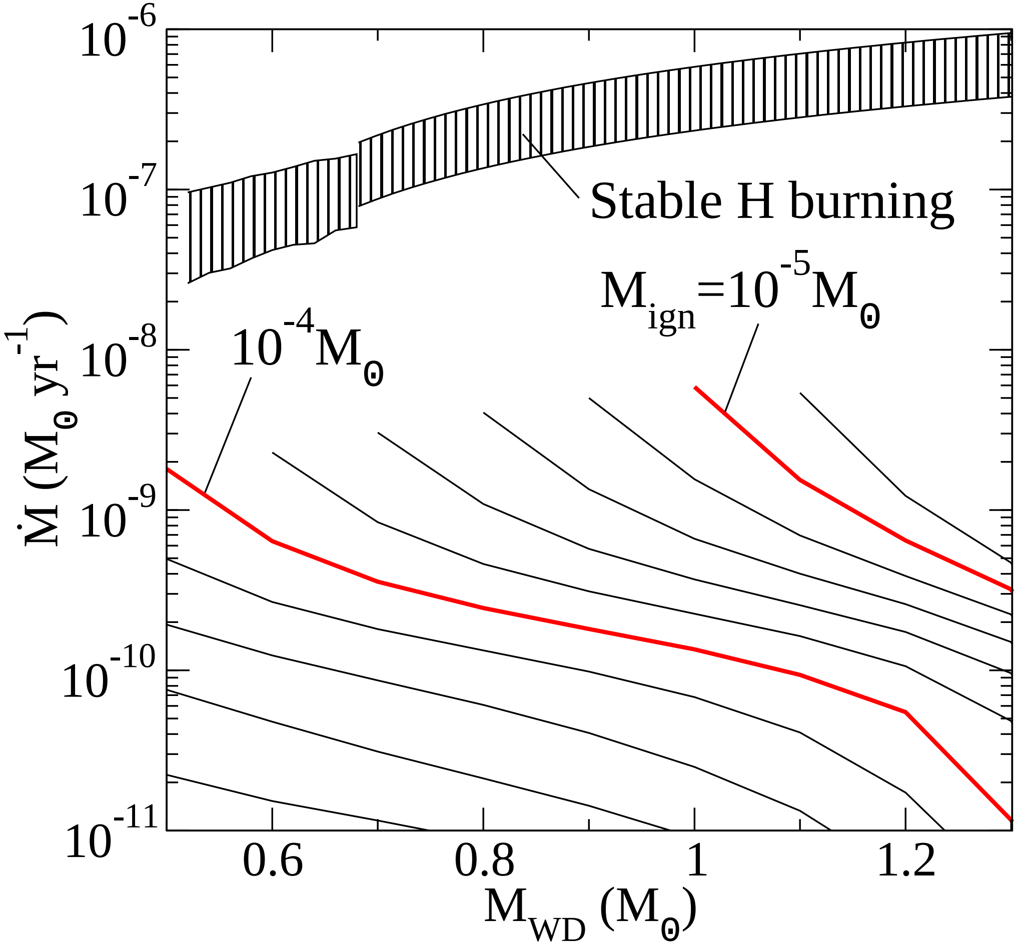
Outburst

$$t_{\rm accretion} \sim \frac{M_{\rm ign}}{\dot{M}_{\rm accrection}} \sim 10^5 - 10^8 \ {\rm yr}$$

$$t_{\rm outburst} \sim \frac{M_{\rm ign}}{\dot{M}_{\rm loss}} \sim \text{days-months}$$

Here I will discuss $M_{\rm ign}$ which is important or both of these phases.
Determination of $M_{\rm ign}$ involves mostly properties of the accretion phase.

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.

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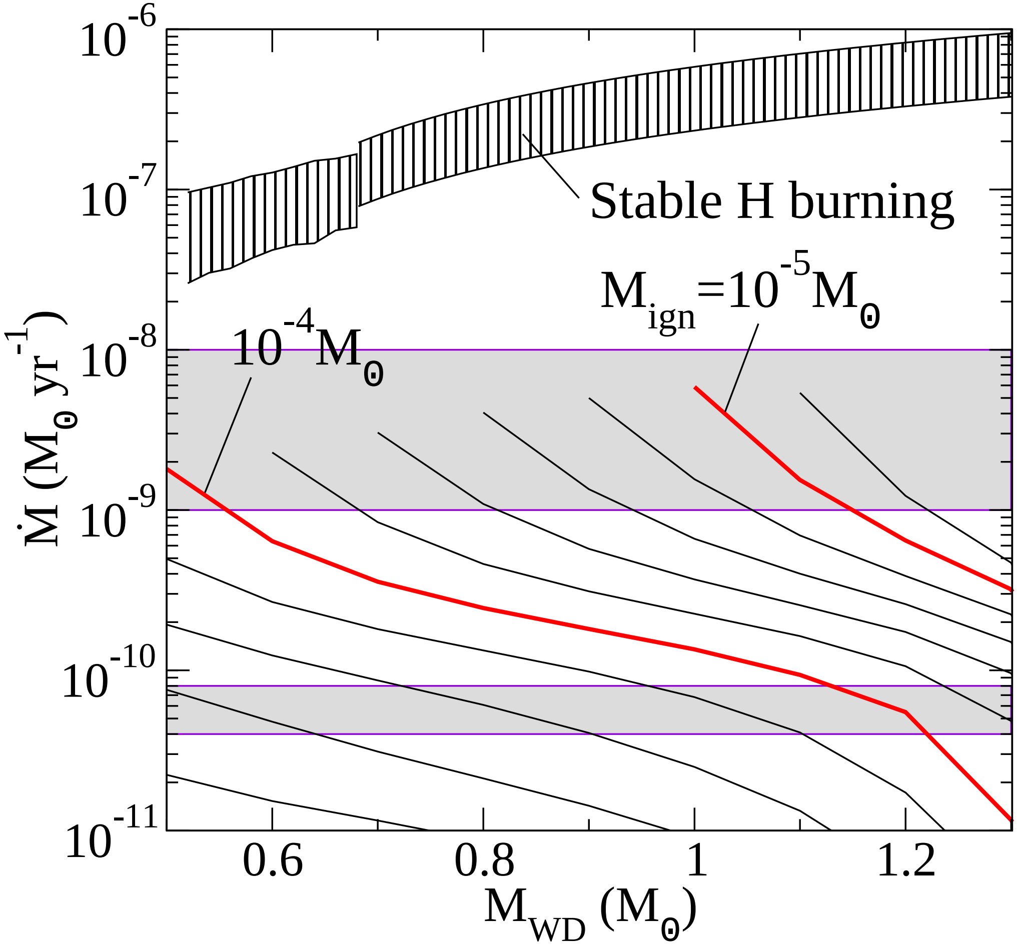

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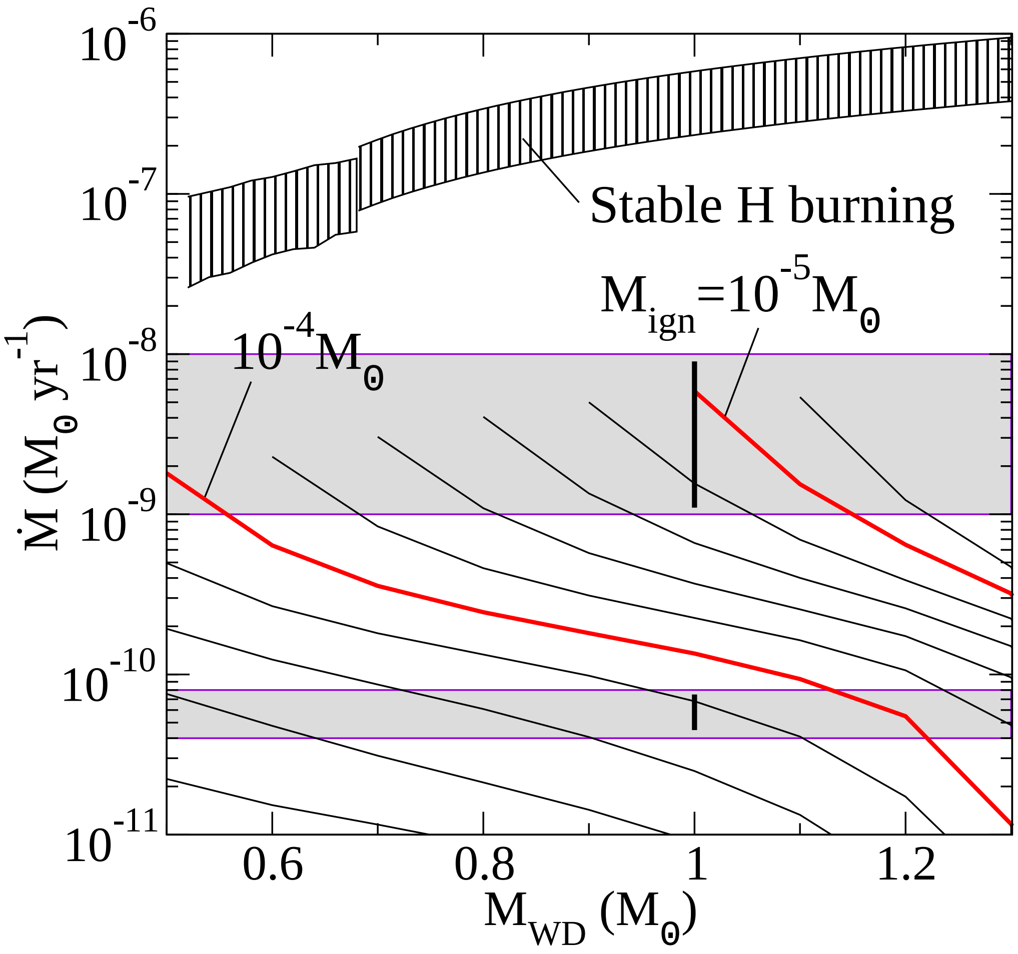

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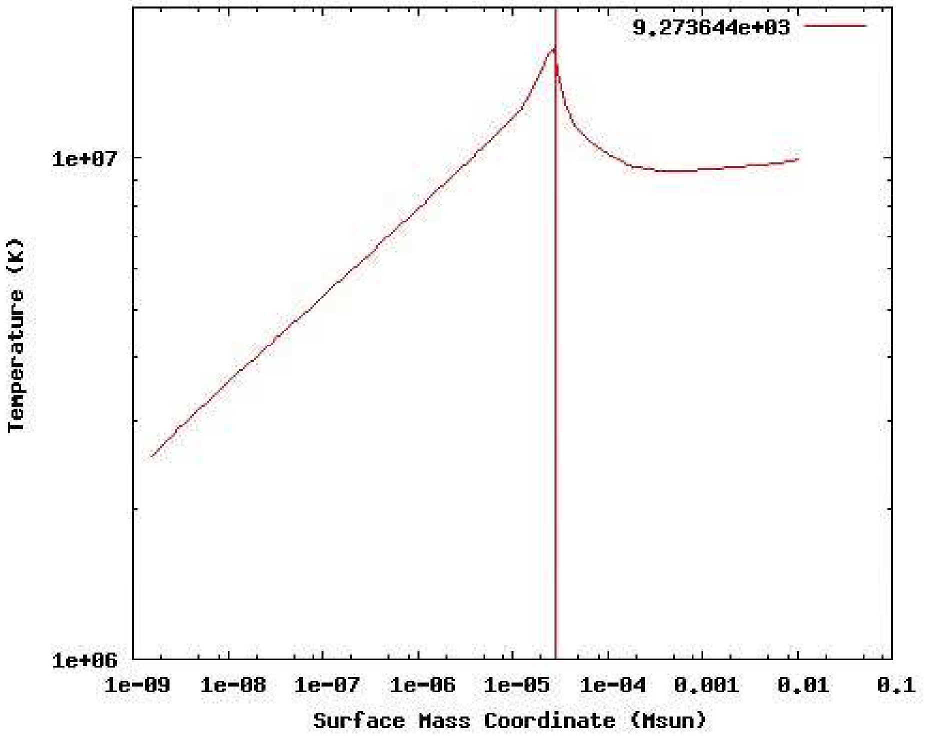
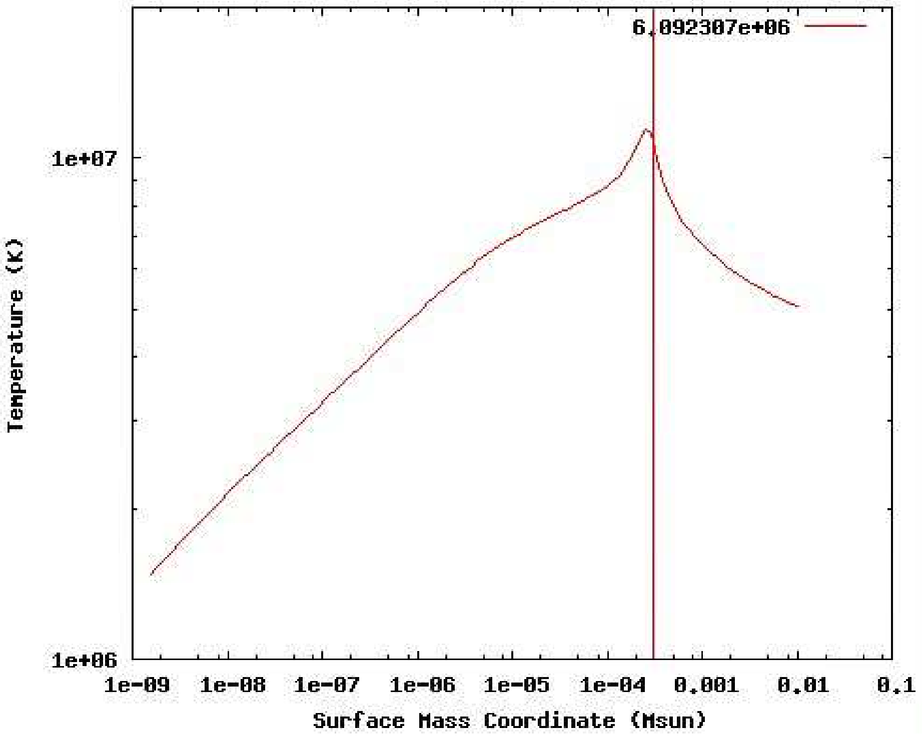
Two Kinds of Ignition





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

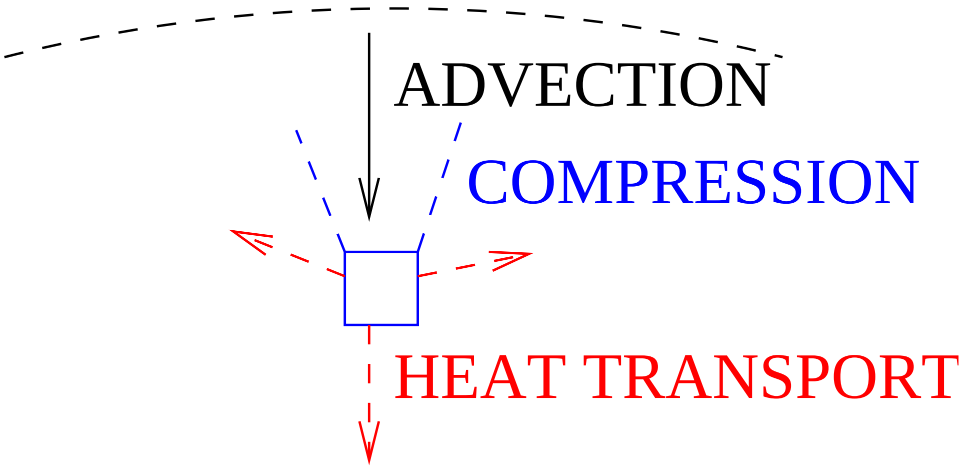
$$\langle \dot{M} \rangle = 5 \times 10^{-11} M_\odot \ \mathrm{yr}^{-1}$$

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

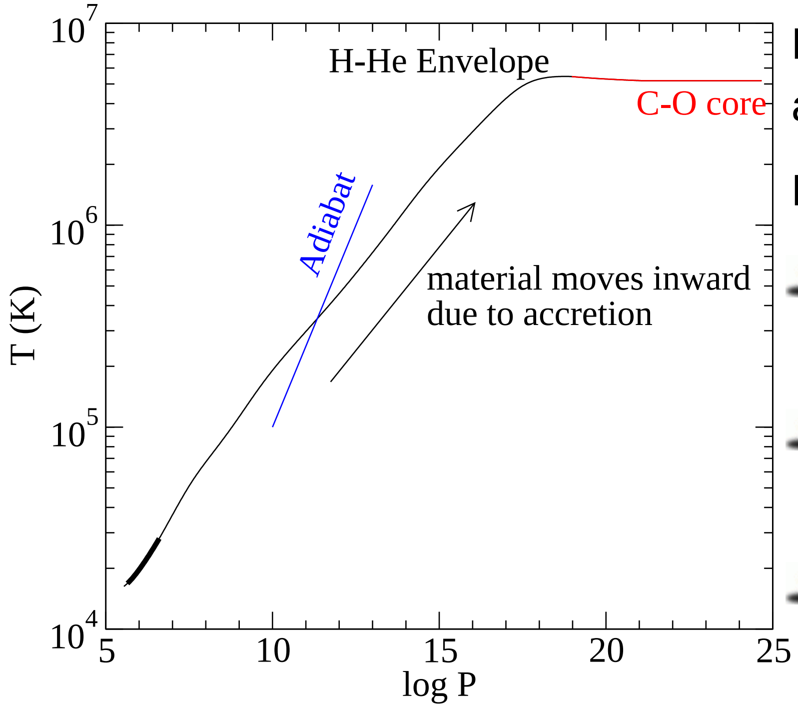
$p + p$ (partial chain) envelope heating eventually leads to $p + \mathrm{C}$

Large accumulated mass

Heat Sources



(very) leaky entropy advection

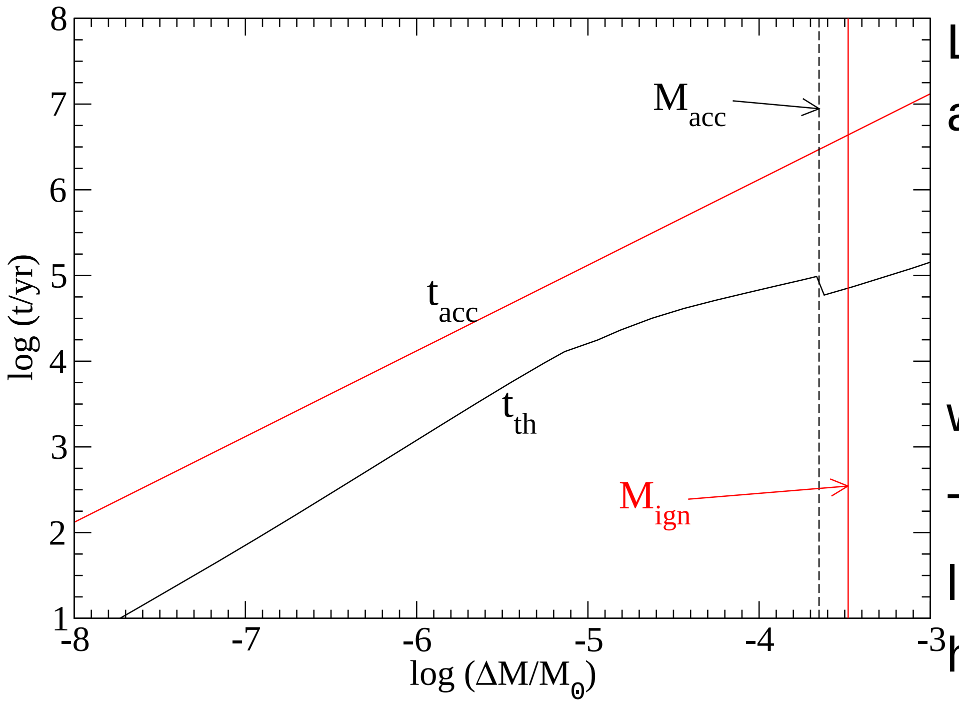


Heat liberated by compression is transferred out to surface and in to core. Often called “compressional heating”.

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

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

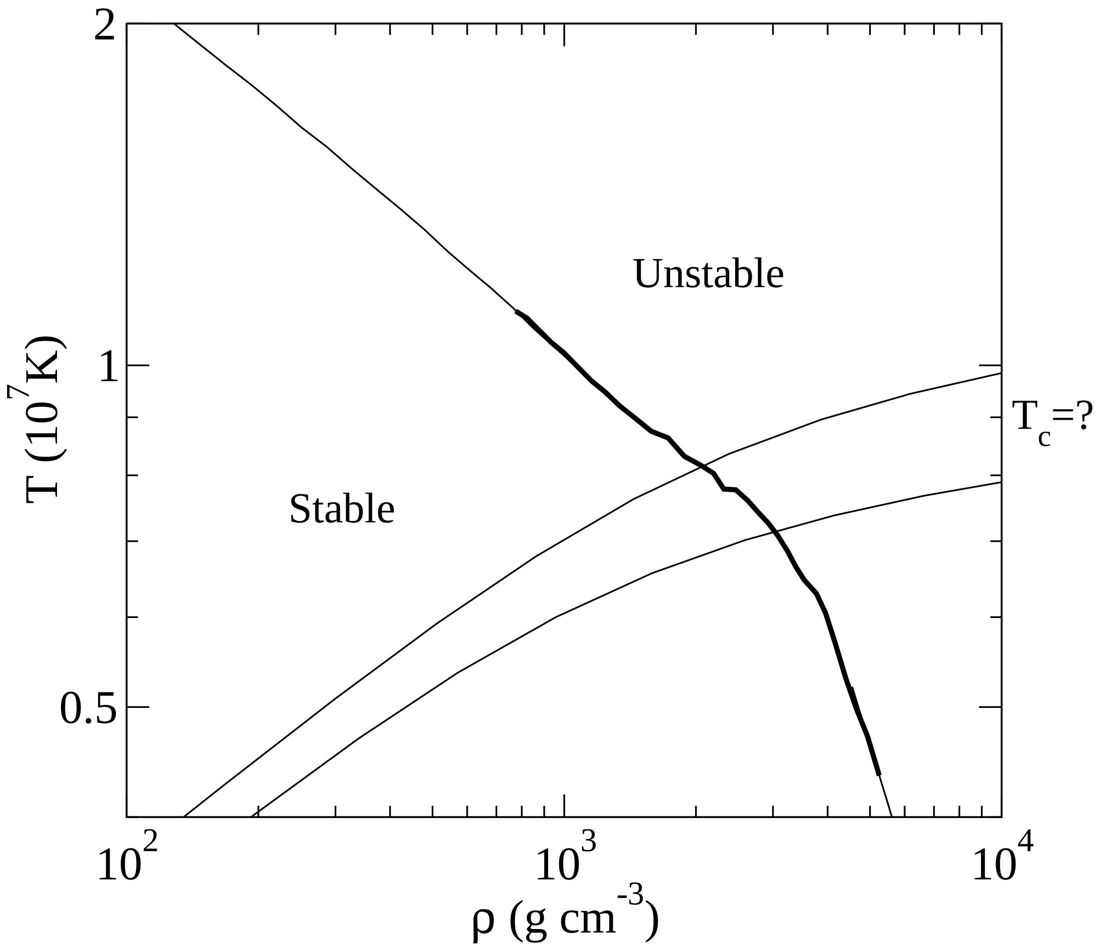
where $v_r = -\langle \dot{M} \rangle / 4\pi r^2 \rho$. Solve with structure equations. Gives excellent representation of envelope sructure.

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

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

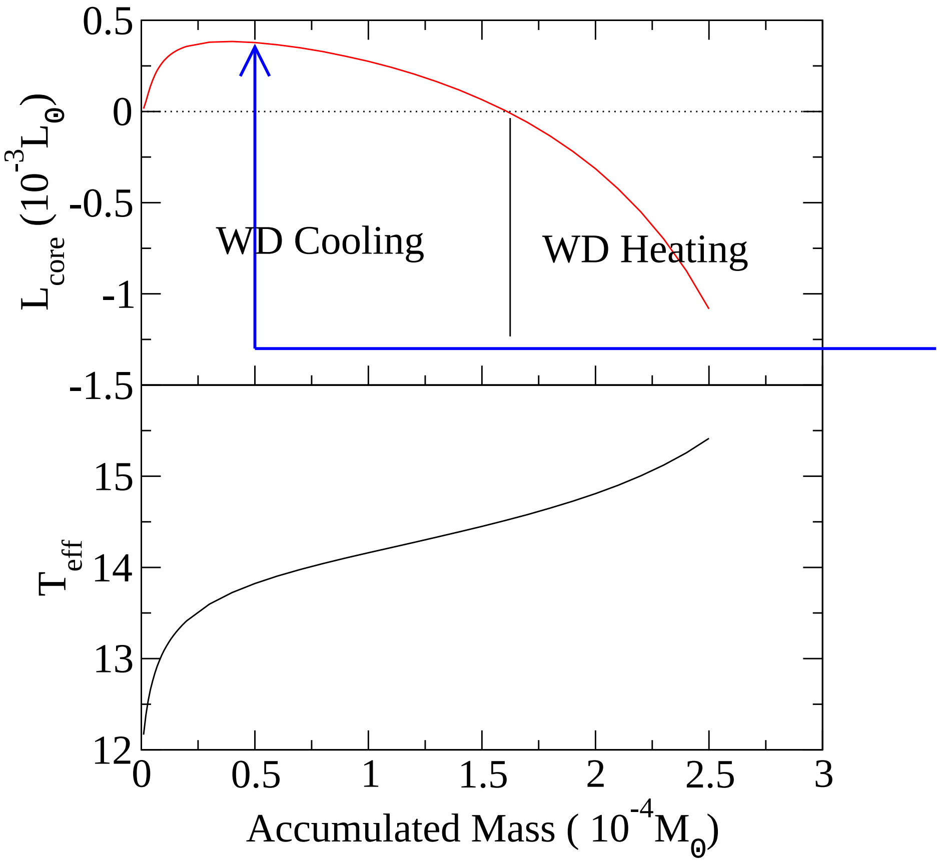


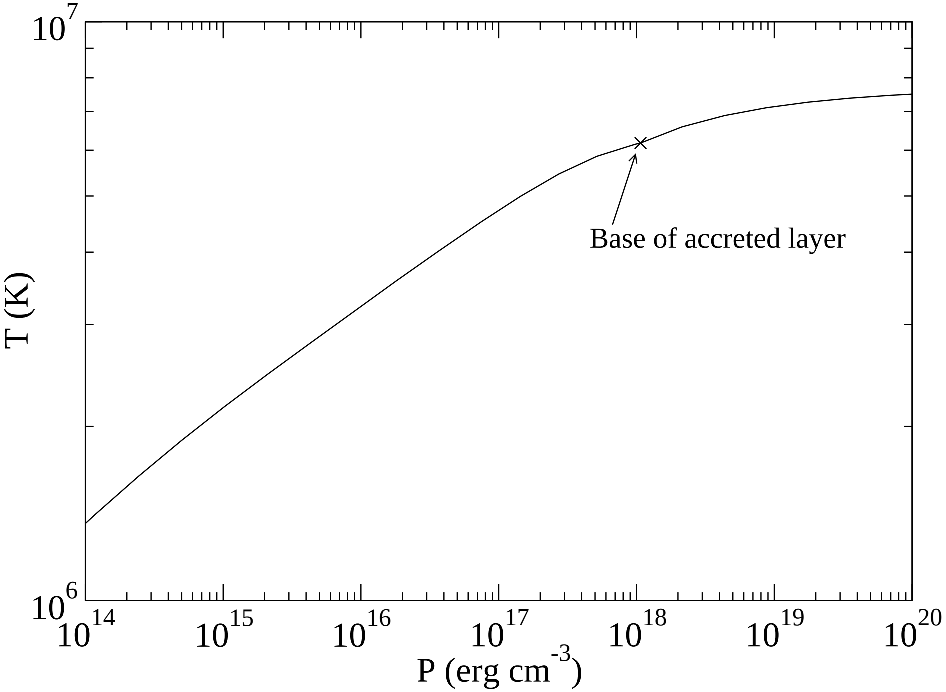
Evaluating envelope stability:

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

- 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

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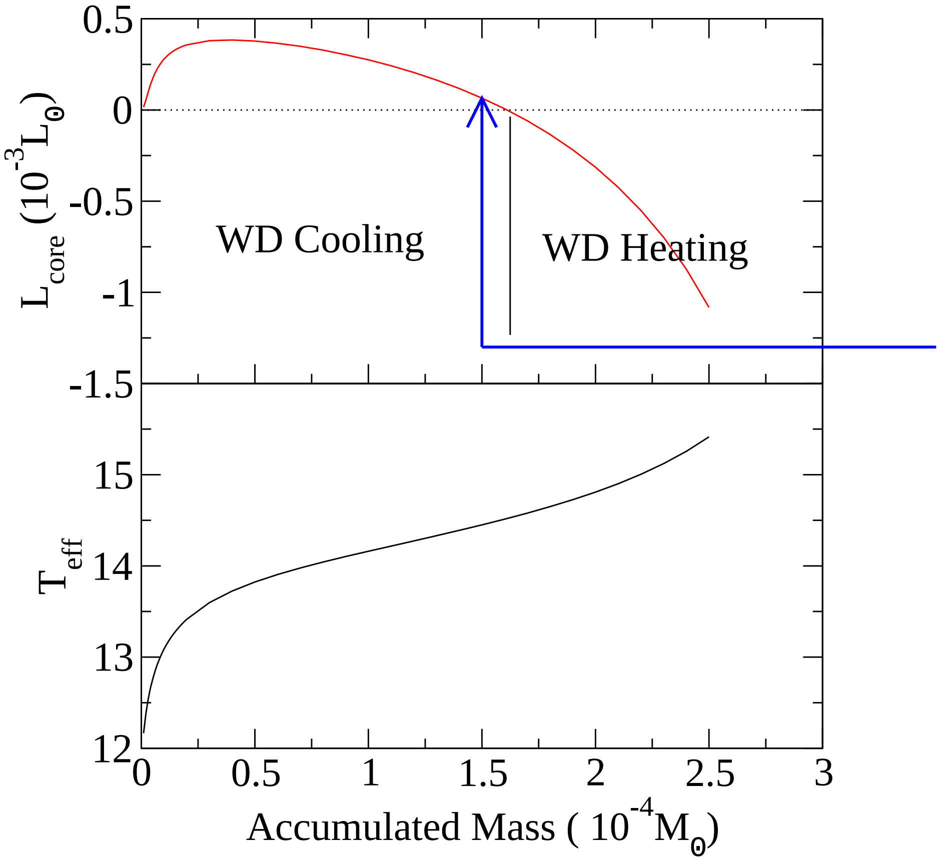

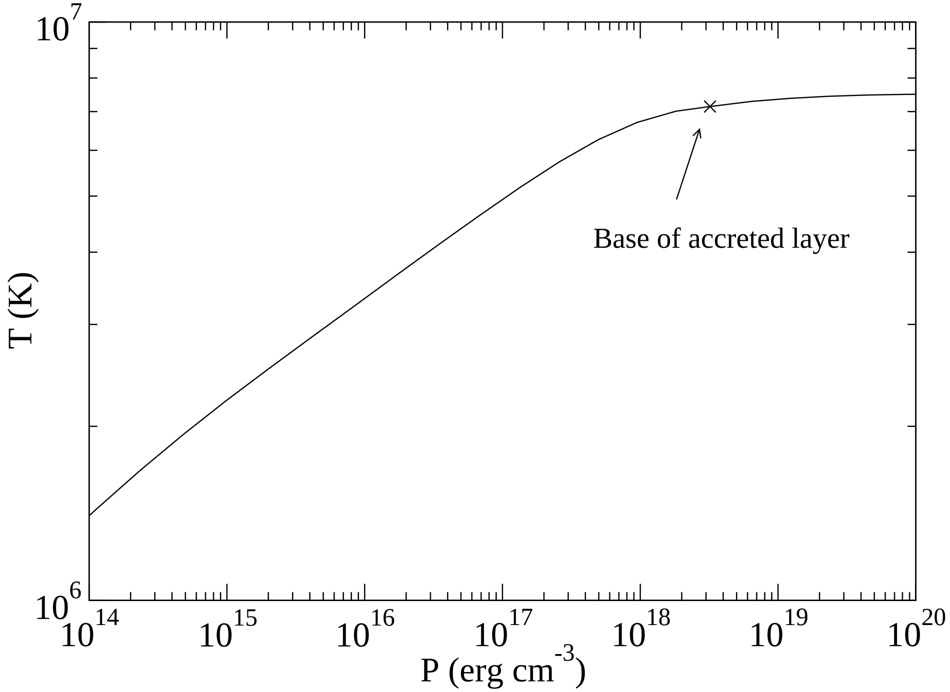

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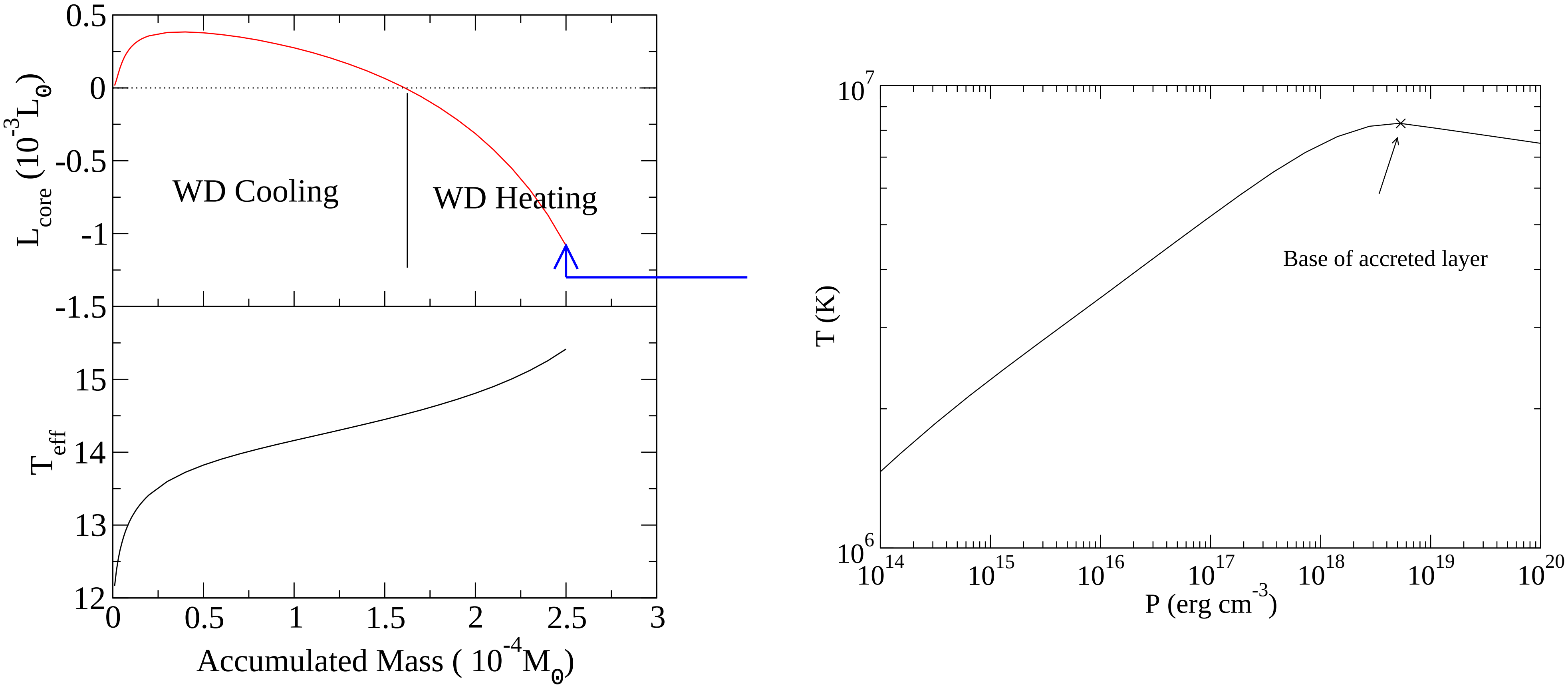

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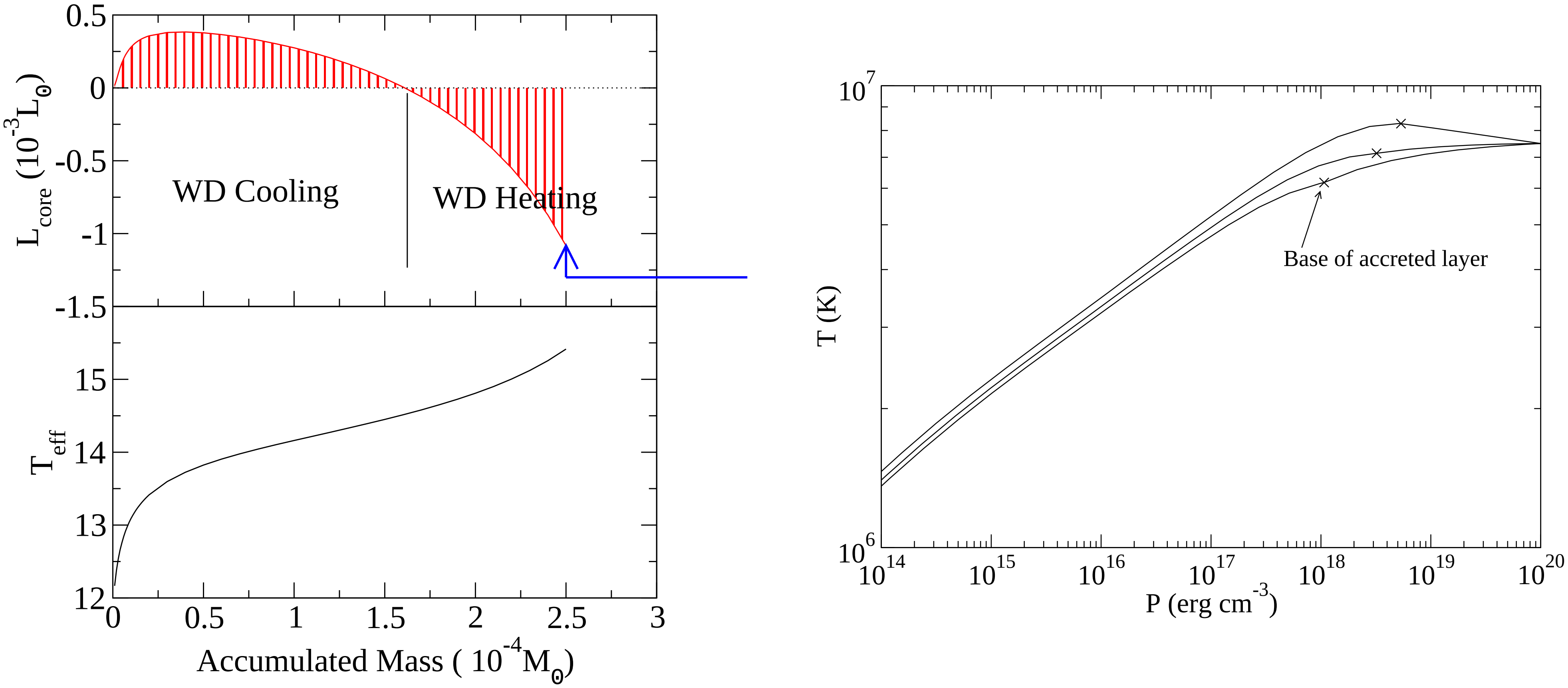

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$$\langle L_{\rm core}\rangle = \frac{1}{t_{\rm CN}}\int_0^{t_{\rm CN}} L_{\rm core}\, dt$$

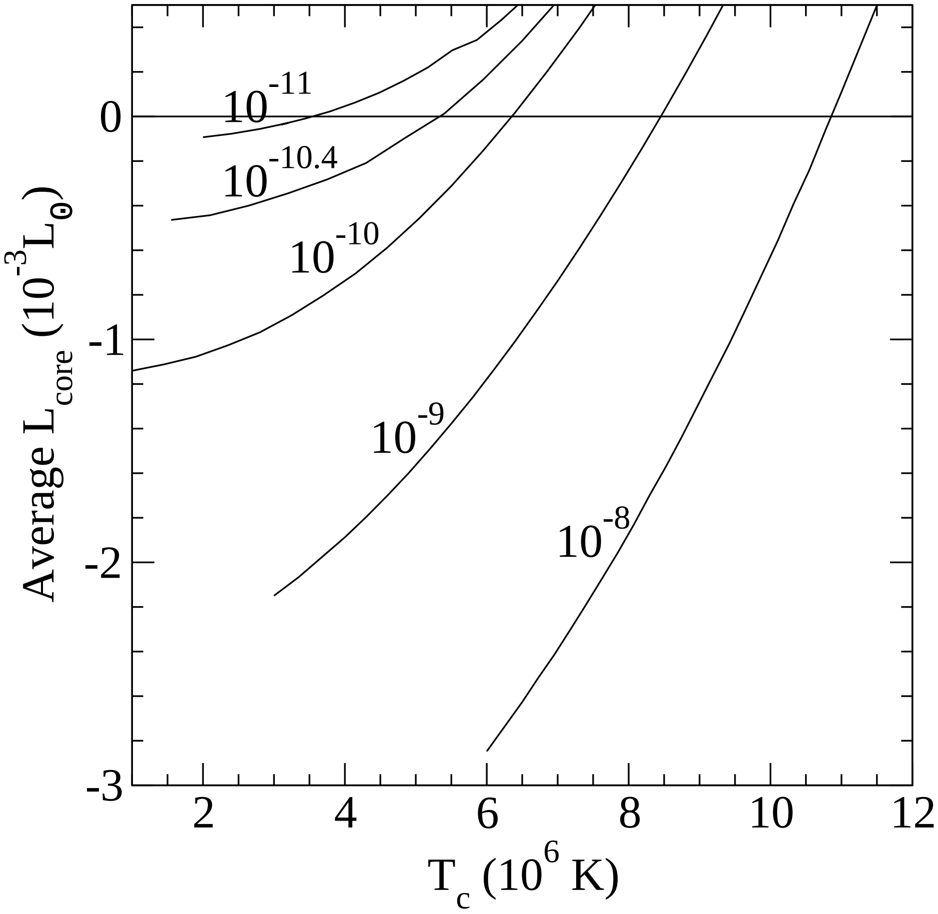
$\langle L_{\rm core}\rangle$ and the equilibrium $T_{\rm core}$

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

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

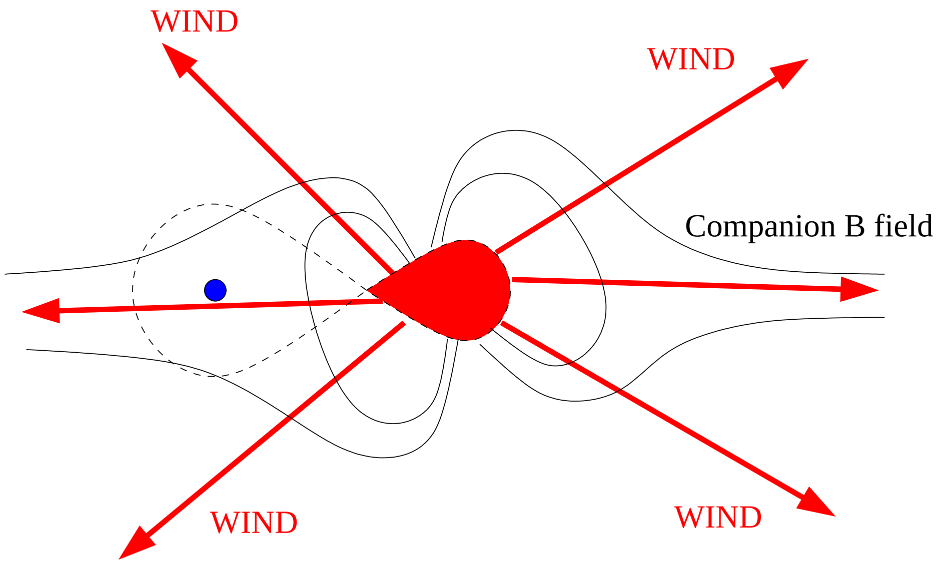
Equilibrium $T_{\rm core}$

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



CV Angular Momentum Loss

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

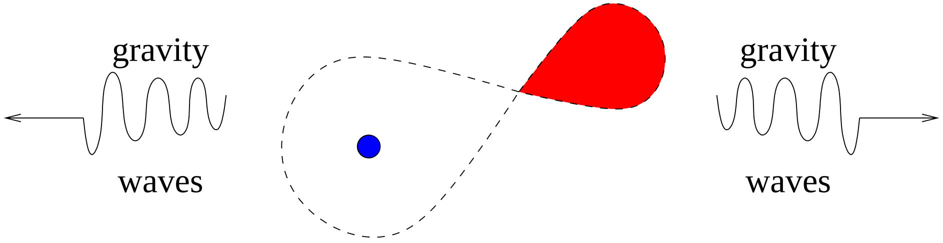


Magnetic Braking

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

Magnetically attached wind from companion star

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

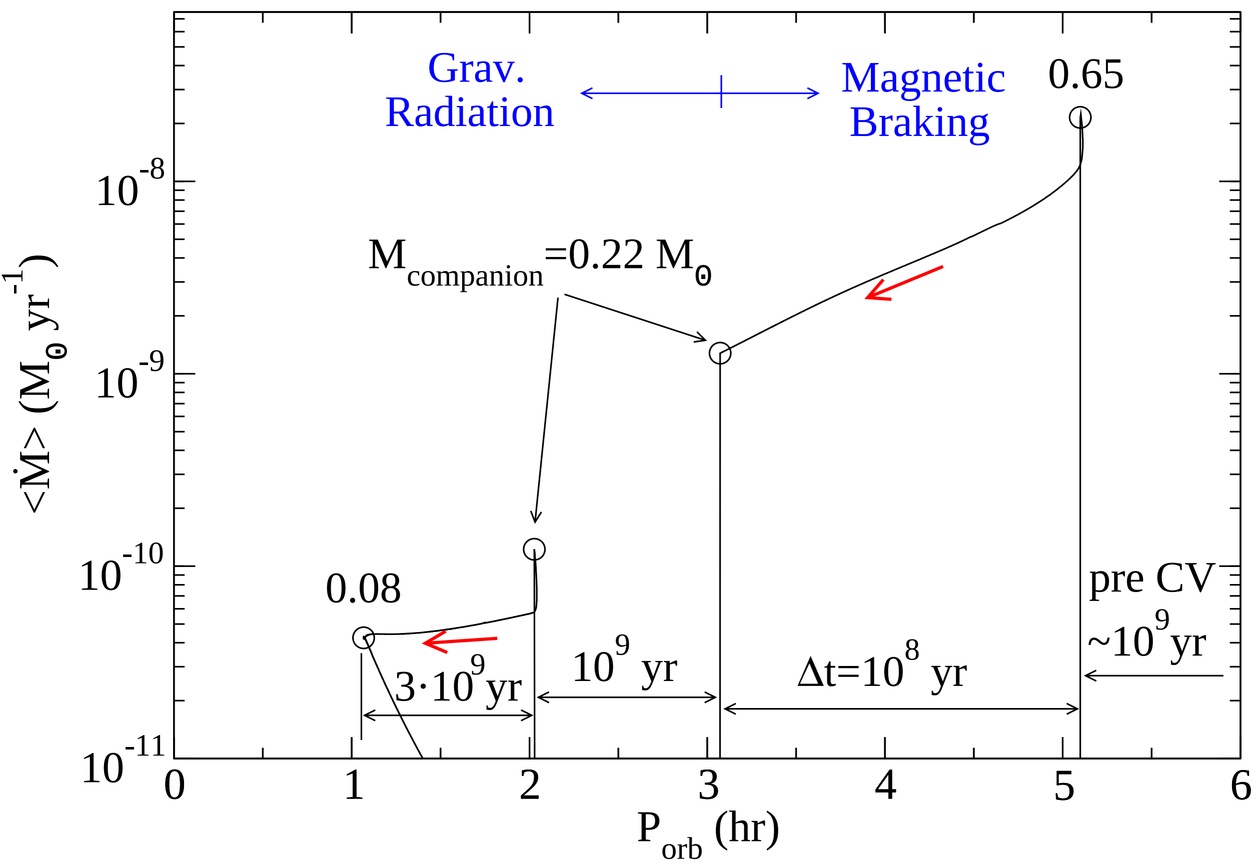


Gravitational Radiation

low $\dot{J}$

$$\begin{aligned} \dot{J}_{\rm gr} &= -\frac{32 G Q^2 \omega^5}{5 c^5} \\ &= -2.7 \times 10^{37}\,{\rm erg} \left(\frac{a}{R_\odot}\right)^4 \left(\frac{M_{\rm WD} M_2}{M_t M_\odot}\right)^2 \left(\frac{P_{\rm orb}}{\rm hr}\right)^{-5} \end{aligned}$$

Interrupted Magnetic (Wind) Braking?



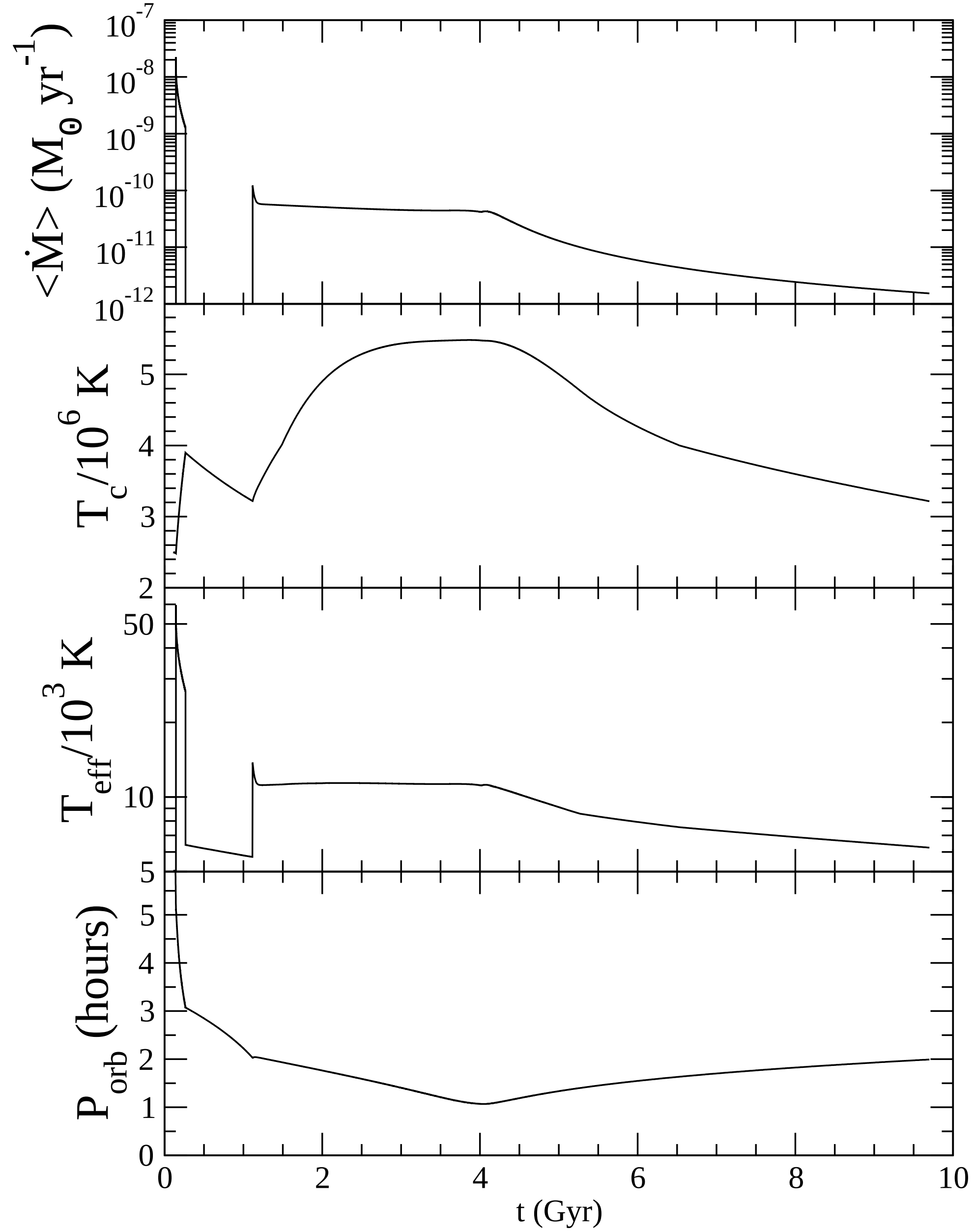
$M_{\rm WD} = 0.7 M_\odot$, Howell, Nelson, & Rappaport 2001, ApJ 550, 897

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)

WD Thermal State Evolution



Phases of accretion

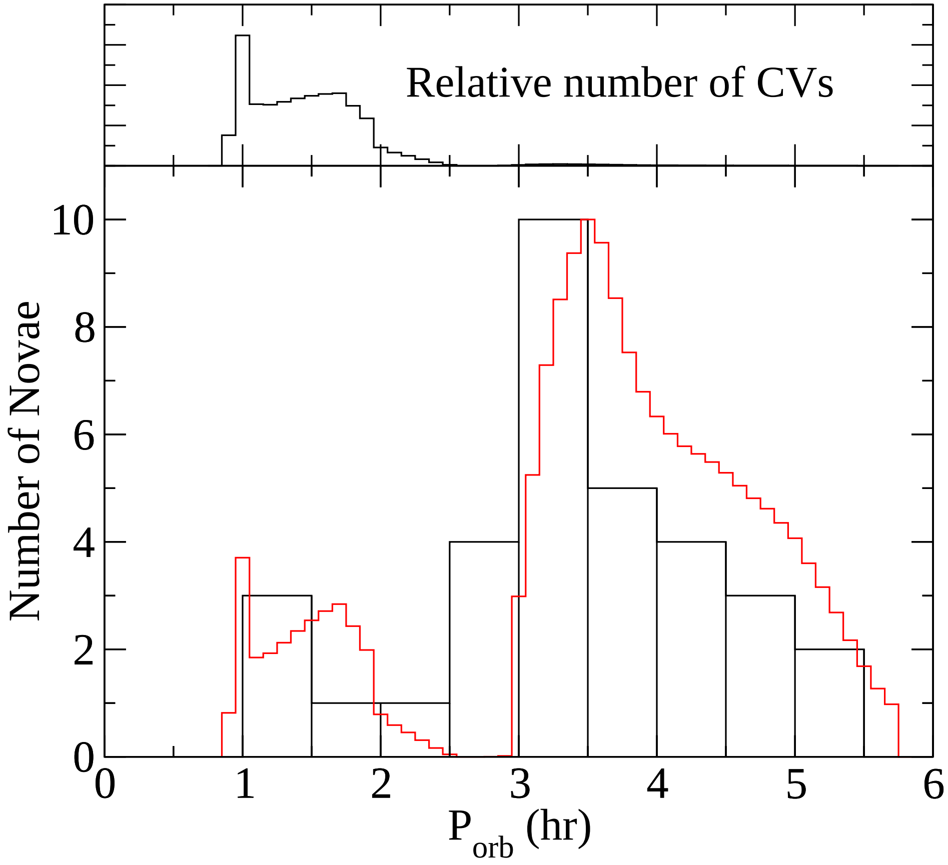
1. Magnetic Braking $\langle \dot{M} \rangle \sim 5 \times 10^{-9} M_\odot\ \mathrm{yr}^{-1}$
2. Period gap $\langle \dot{M} \rangle = 0$
3. Gravitational radiation $\langle \dot{M} \rangle \simeq 5 \times 10^{-11} M_\odot\ \mathrm{yr}$
4. Post-period minimum $\langle \dot{M} \rangle < 10^{-11} M_\odot\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

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



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)

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

- 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

Summary

- Compression of envelope material by accretion sets envelope thermal structure
- CV evolution sets T_c frome $\langle \dot{M} \rangle$ – leaves two parameters, $\langle \dot{M} \rangle$, M and composition
- Relative nova rate with orbital period reproduced by canonical interrupted magnetic braking CV scenario

Open Questions

- Relative role of enrichment from carbon-rich core material before vs. during the runaway
- Is scatter in maximum magnitude-rate of decline relation from $\langle \dot{M} \rangle$?
- Mass evolution of primary
- Does the outburst ignition type have ramifications for nucleosynthesis during outburst – Currently under investigation