Hydrogen Burning on Accreting White Dwarf Stars

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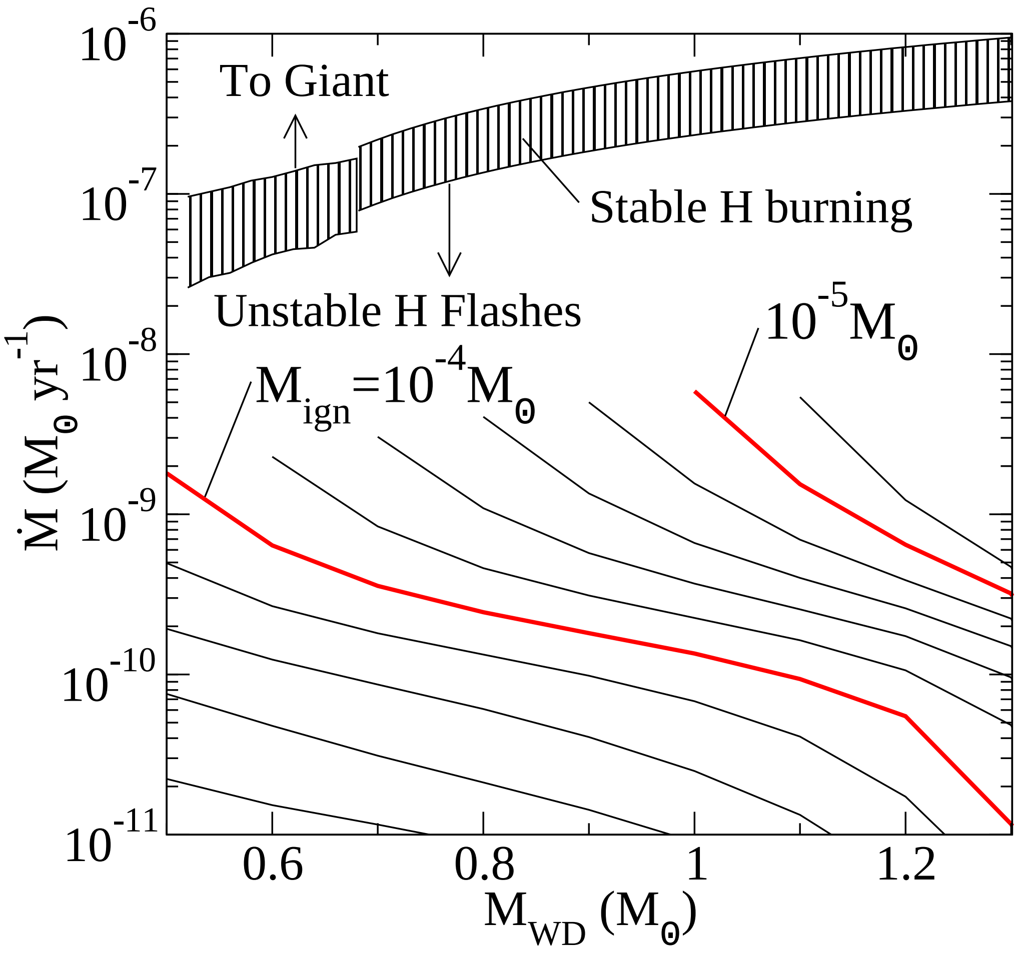
Motivation

- What do outbursts say about underlying system properties and evolution?
- Want to constrain short period binary population:
  angular momentum loss, mass distributions, period distributions
- Essential information for understanding SN Ia population and its history

Outline

- Burning modes on accreting WDs
- How these arise in the binary population
- Stable Buring
  - Thermal timescale mass transfer and "Supersoft" X-ray sources
  - Type Ia progenitors
- Unstable flashes - Novae
  - Evolution of Nova binaries
  - Thermal evolution of WD and equilibrium T_c
  - Ignition and $\langle \dot{M} \rangle$ – the role of CNO and pp burning
  - Nova breakout nucleosynthesis
- Open questions

Accretion and Burning Modes

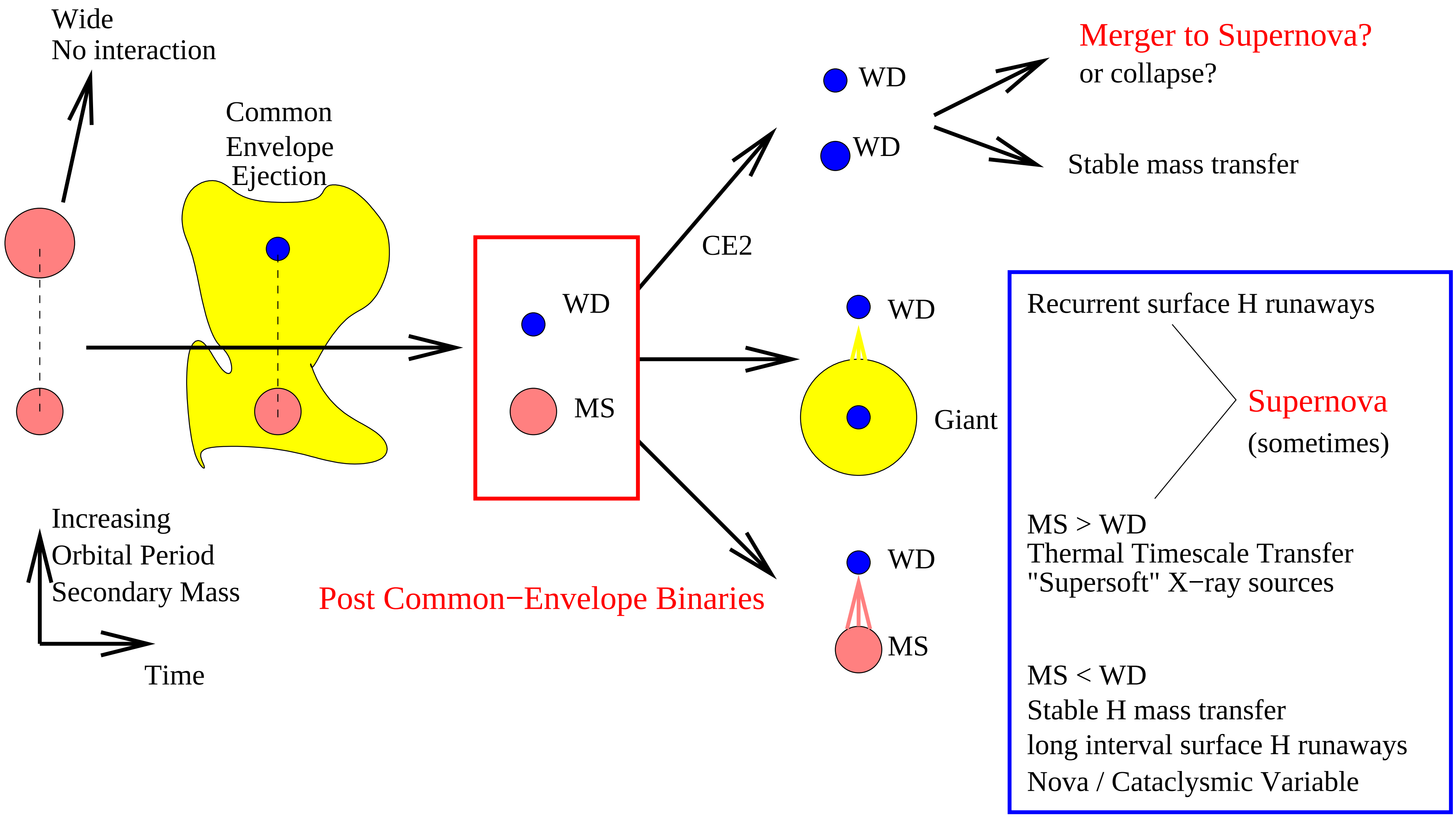


Contours spaced by $\Delta \log(M_{\rm ign}/M_\odot) = 0.2$

Townsley & Bildsten 2005, ApJ, 628, 395

- High (but not too high) $\langle \dot{M} \rangle$ leads to steady burning. Soft X-ray source.
- Lower $\langle \dot{M} \rangle$ gives periodic (10 to 10^8 yr) H-burning flashes. Novae.
- Growth to giant prevented by wind-driven mass loss (?)

WD Binary Formation



Wide
No interaction

Common
Envelope
Ejection

Increasing
Orbital Period
Secondary Mass

Time

WD

MS

Post Common−Envelope Binaries

CE2

WD

WD

Merger to Supernova?
or collapse?

Stable mass transfer

WD

Giant

WD

MS

Recurrent surface H runaways

Supernova
(sometimes)

MS > WD
Thermal Timescale Transfer
"Supersoft" X−ray sources

MS < WD
Stable H mass transfer
long interval surface H runaways
Nova / Cataclysmic Variable

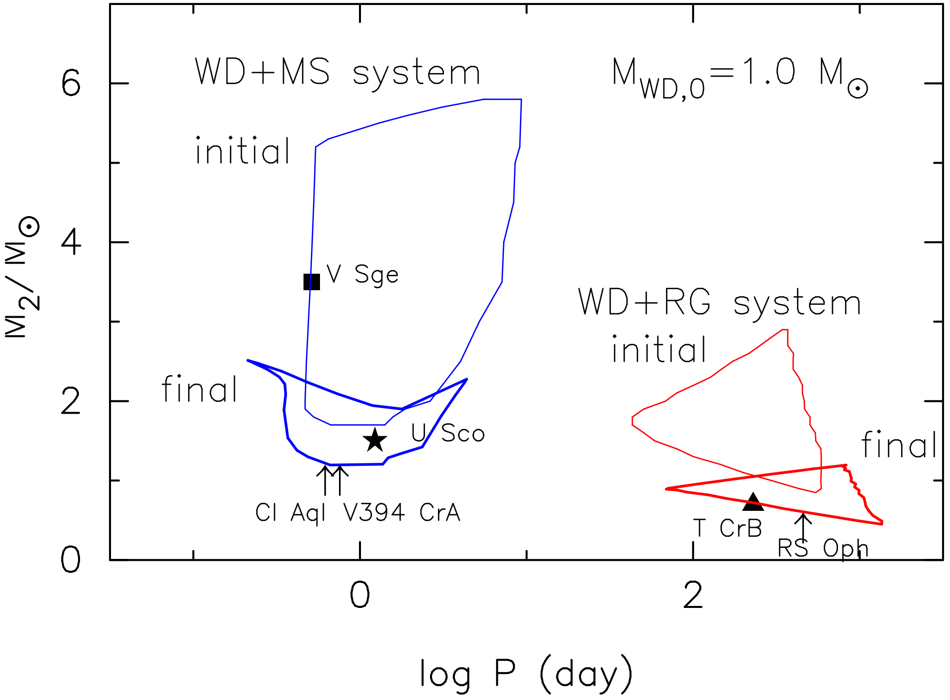
Main Type Ia Channel: MS star mass $>$ WD mass – Thermal Timescale Mass Transfer

SSS and Type Ia Progenitors

- Enclosed regions – possible SN Ia progenitors and their evolution
- Points – select SSS and "Recurrent" Nova (~ 10 yr) systems

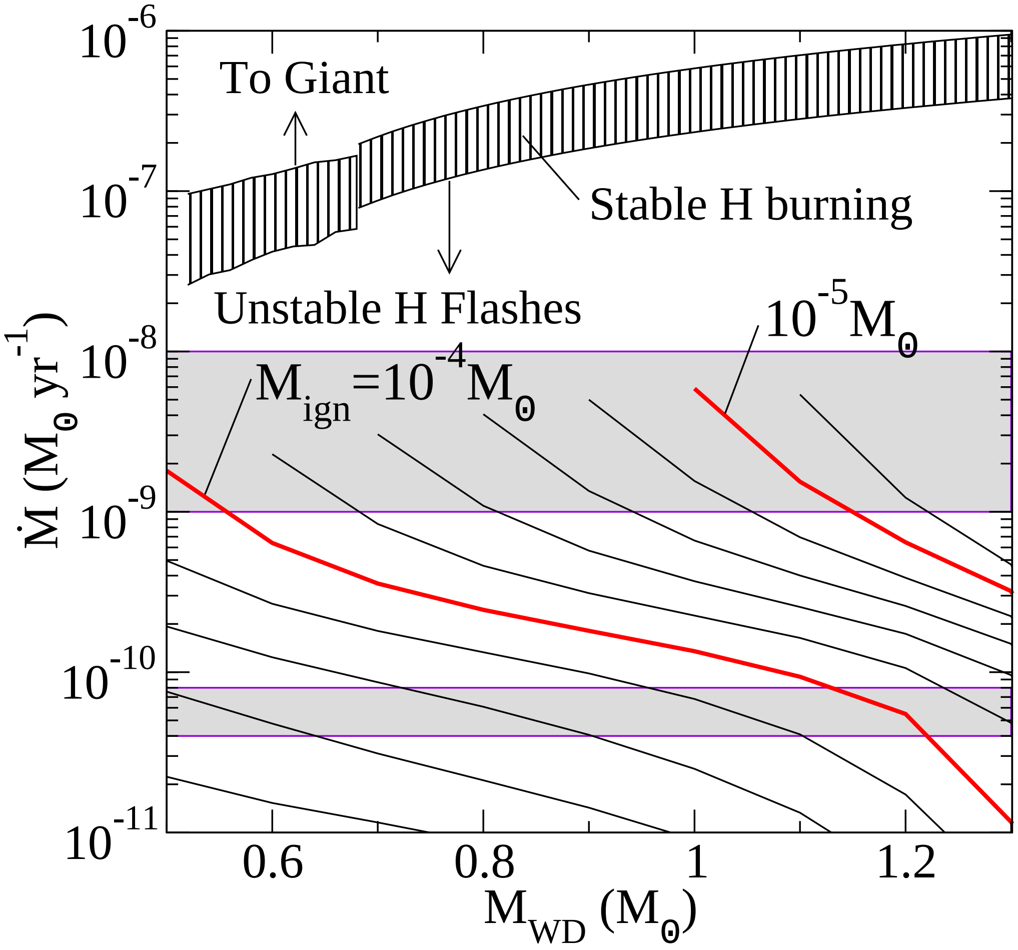
Not a perfect story

- SN Ia remnant environments not entirely consistent with assumed wind mass loss
- Not all become SN Ia, requires fairly massive C+O WD
- Period and mass distributions still fairly uncertain



Hachisu, Kato, & Nomoto 2008, ApJ, 683, L127

Nova Parameter Space



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

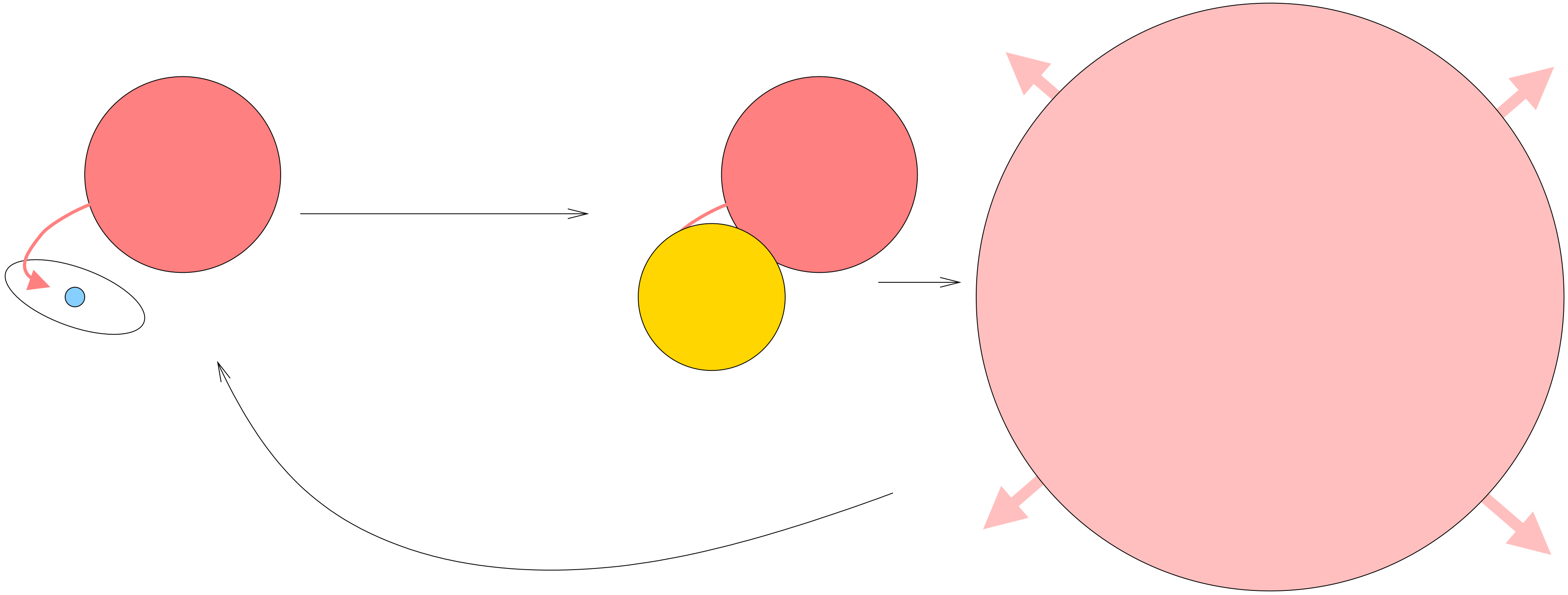
Townsley & Bildsten 2005, ApJ, 628, 395

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.

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).

Nova Accretion and Outburst



Accretion

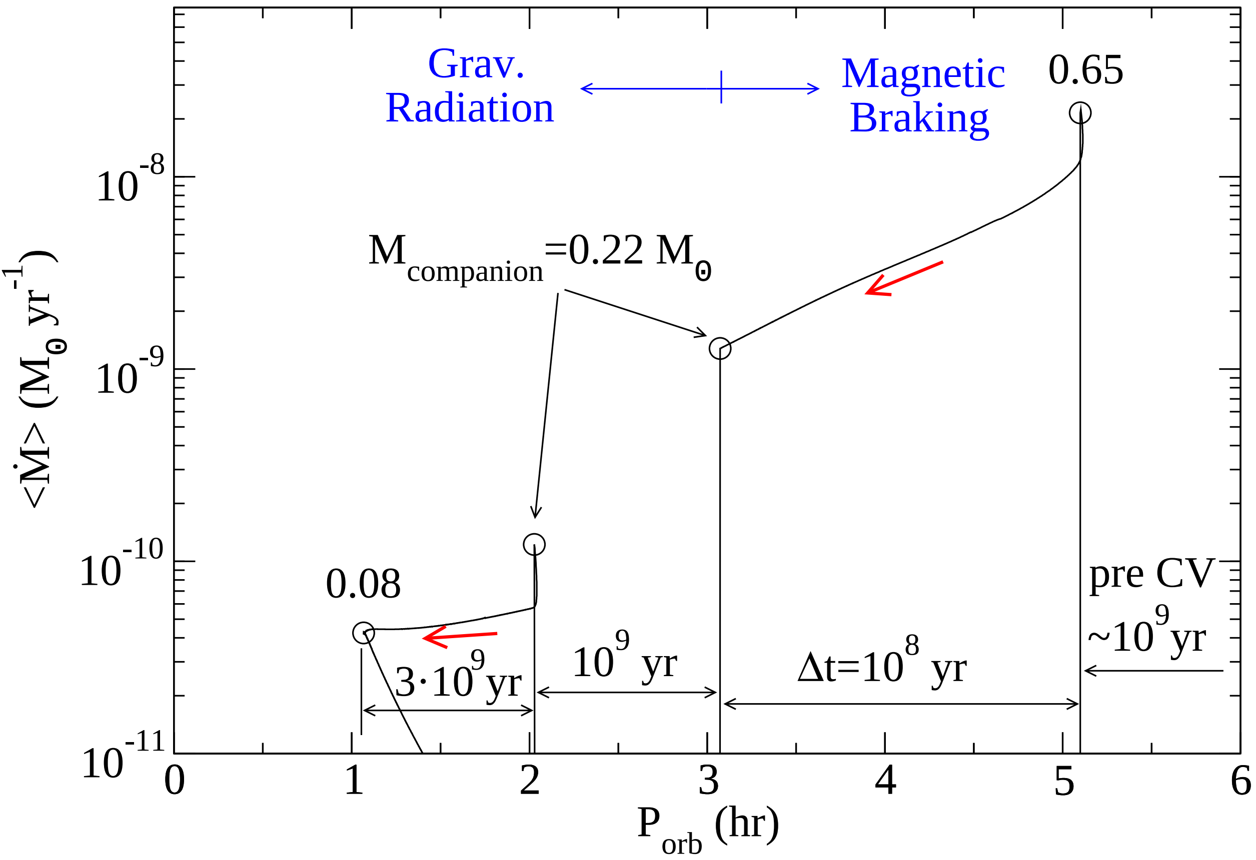
Outburst

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

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

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

Interrupted Magnetic (Wind) Braking?



$M_{\mathrm{WD}} = 0.7M_\odot$, 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.

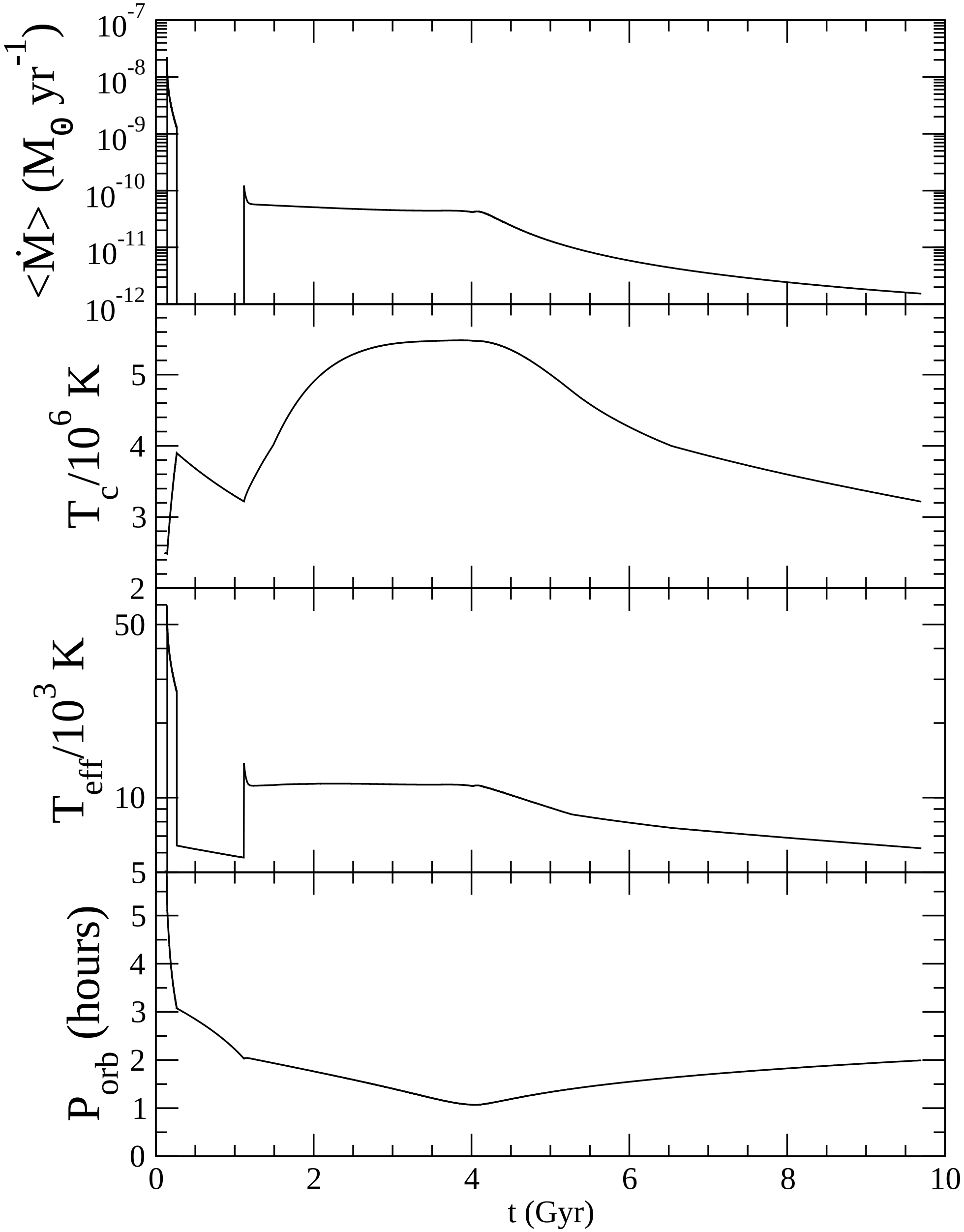
Period gap caused by sudden drop in angular momentum loss rate.

- 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_{eff}.

(Townsley & Bildsten 2003, ApJ, 596, L227;

Townsley & Gänsicke 2009, ApJ, 693, 1007)

WD Thermal State Evolution



Phases of accretion

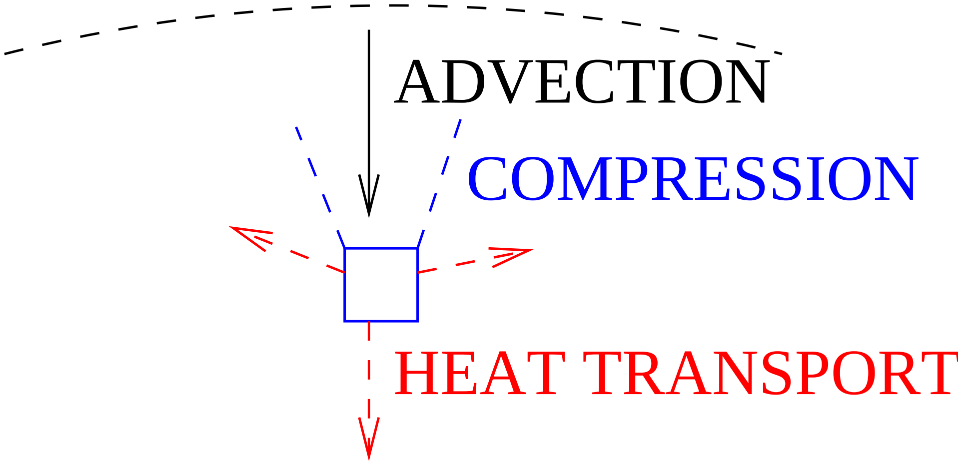
1. Magnetic Braking $\langle \dot{M} \rangle \sim 5 \times 10^{-9} M_\odot\ \mathrm{yr}^{-1}$
2. Period gap $\langle \dot{M} \rangle = 0$
3. Gravitational radiation $\langle \dot{M} \rangle \simeq 5 \times 10^{-11} M_\odot\ \mathrm{yr}$
4. Post-period minimum $\langle \dot{M} \rangle < 10^{-11} M_\odot\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

Phases of WD evolution

1. Reheating – $T_{\rm eff}$ 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 cooling

Heat Sources

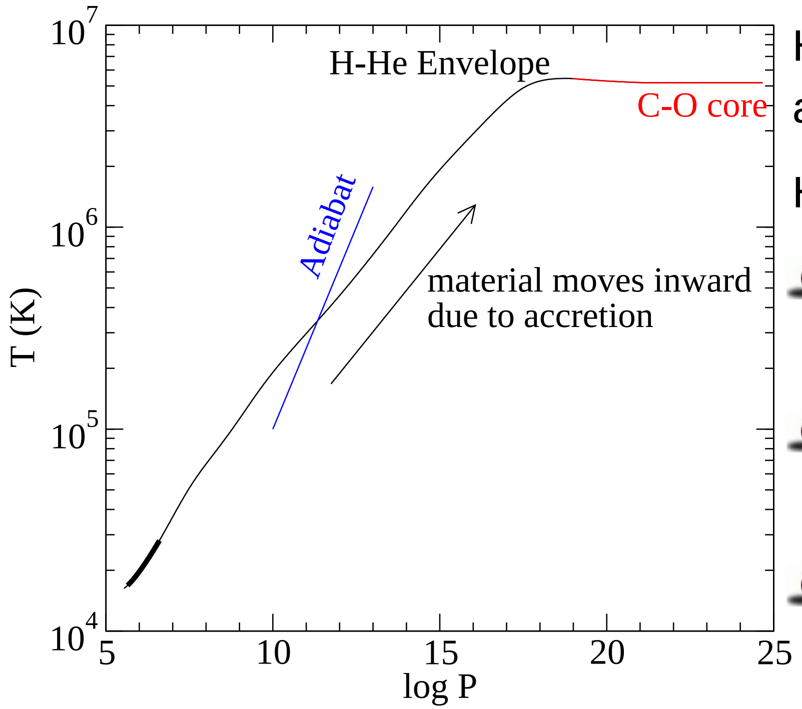


ADVECTION

COMPRESSION

HEAT TRANSPORT

(very) leaky entropy advection

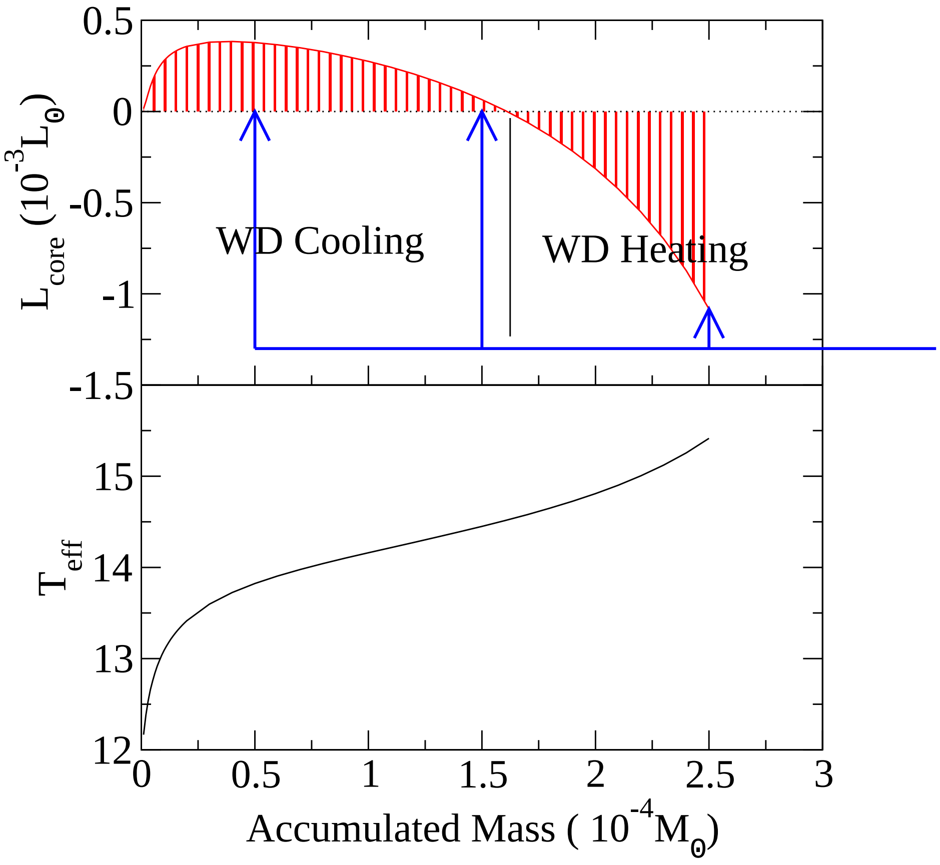


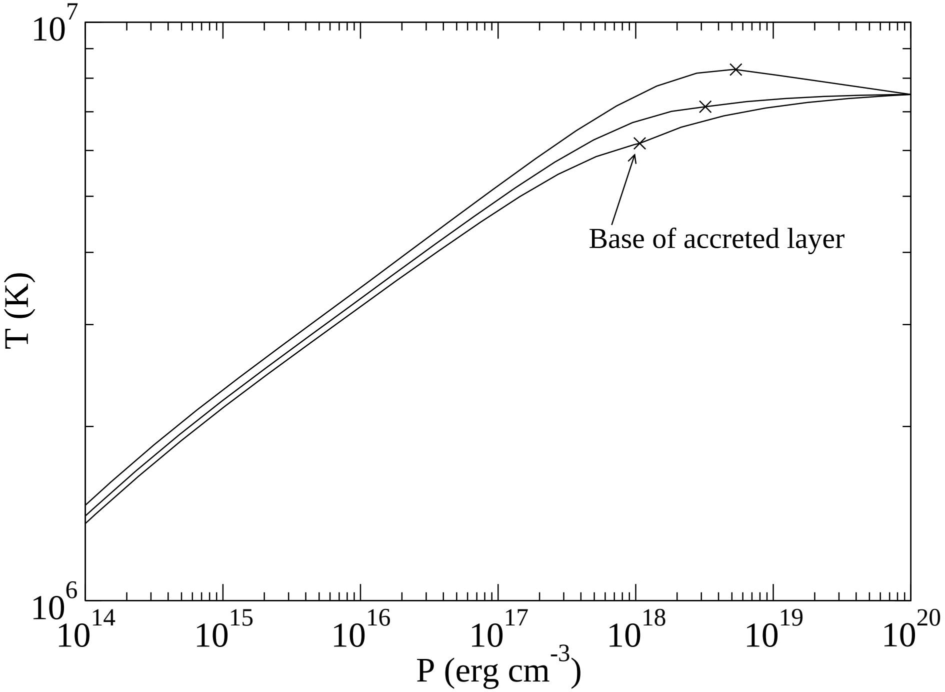
Heat liberated by compression is transferred out to surface and in to core. Often called “compressional heating”.

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

Cooling/Heating Cycle





Townsley & Bildsten 2004, ApJ, 600, 390

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

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

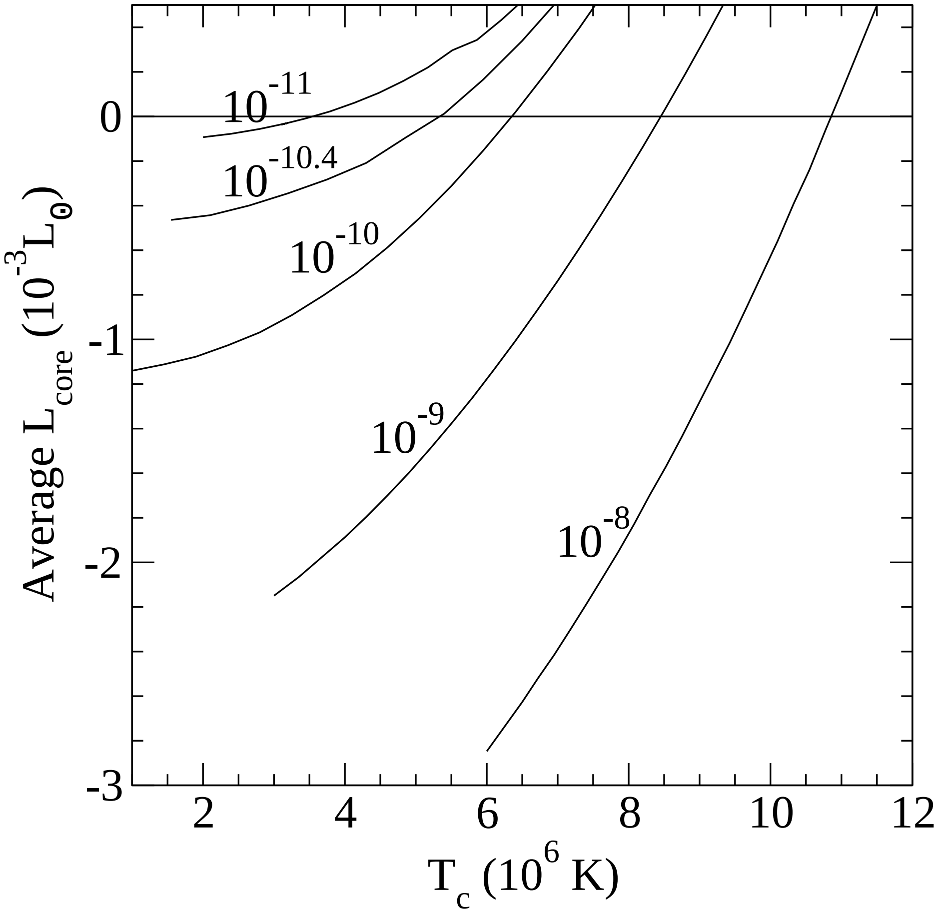
$\langle L_{\rm core}\rangle$ and the equilibrium $T_{\rm core}$

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

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

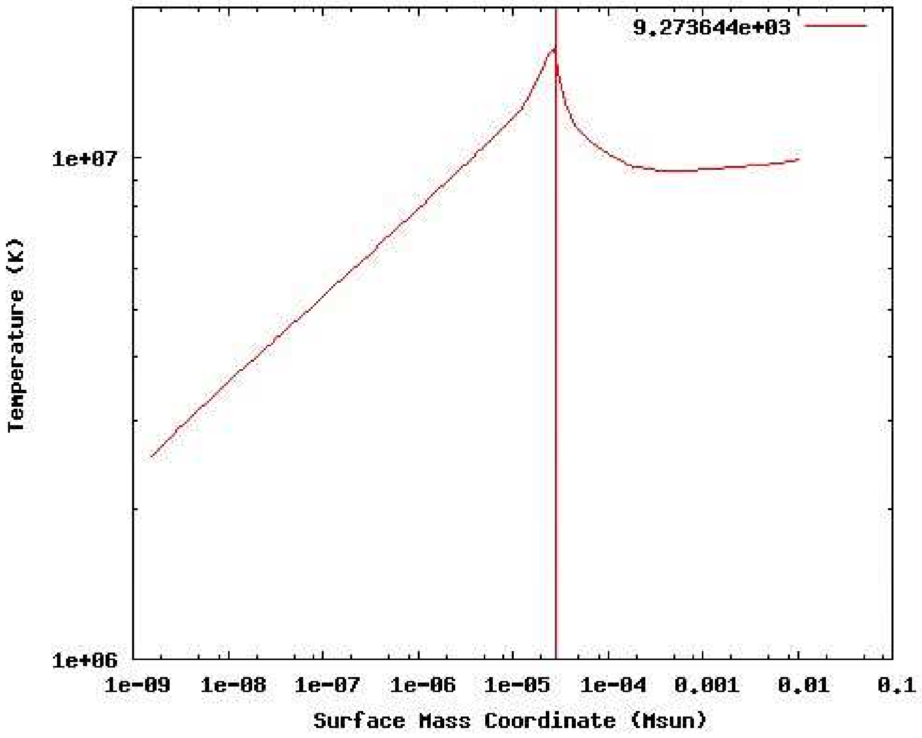
Equilibrium $T_{\rm core}$

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



Townsley & Bildsten 2004, ApJ, 600, 390

Two Kinds of Ignition

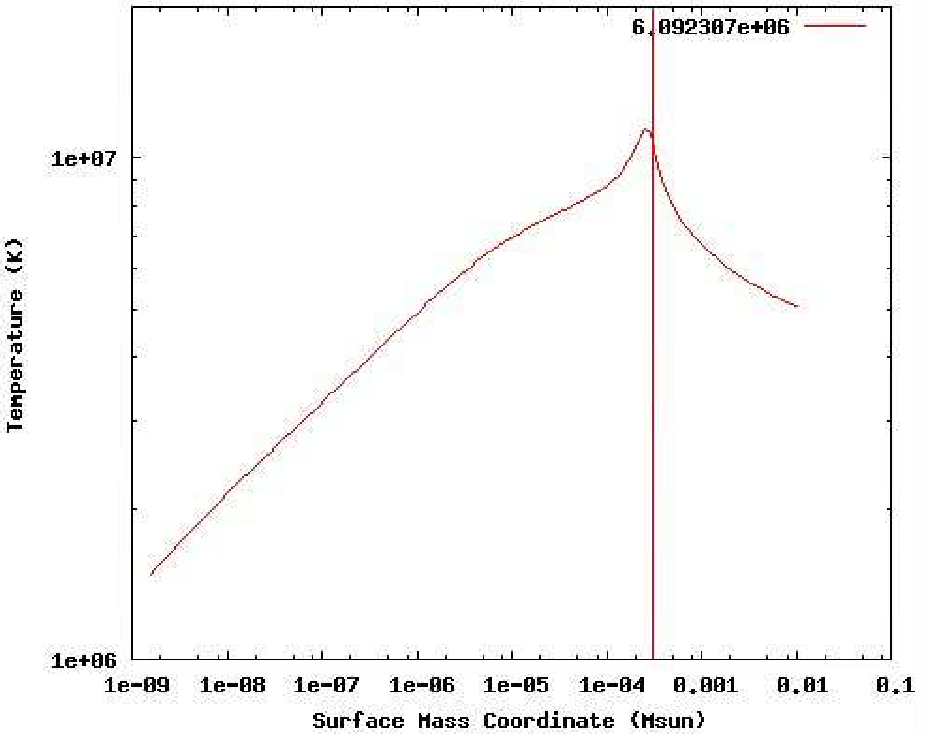


$$\langle \dot{M} \rangle = 3 \times 10^{-9} M_\odot \ \mathrm{yr}^{-1}$$

$$T_c = 10^7$$

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

Most novae by number



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

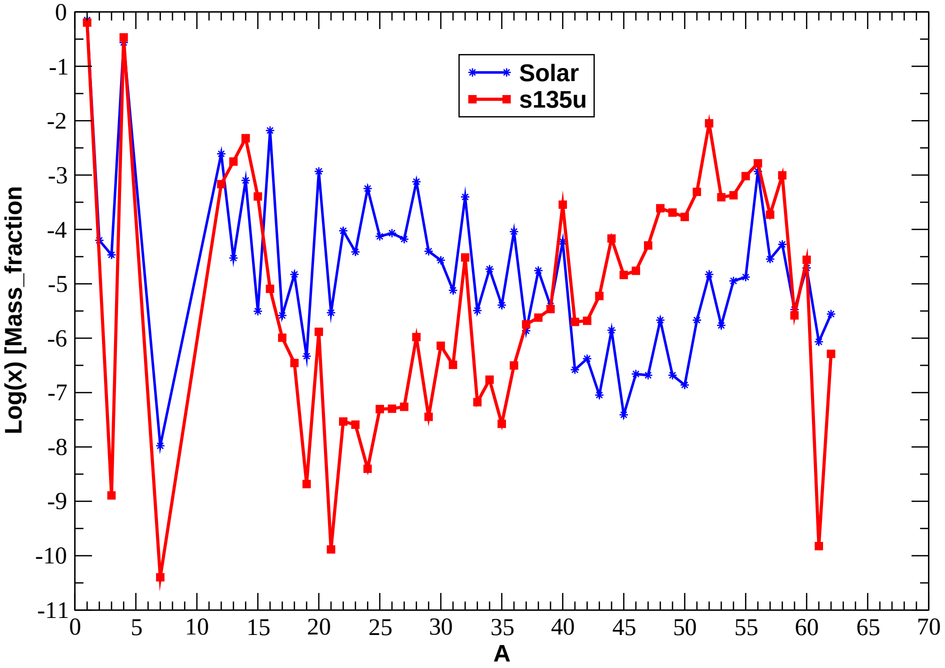
$$T_c = 5 \times 10^7$$

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

Large accumulated mass

CNO Cycle Breakout

- Burning above $\approx 4 \times 10^8$ K can synthesize elements heavier than Oxygen
- Need high degeneracy at runaway
- Does not occur with $T_c \gtrsim 10^7$ K assumed in many Nova calculations
- Occurs for WDs above $1.25 M_\odot$ at low $\langle \dot{M} \rangle$ and equilibrium T_c
- Alternative to dredge-up for certain abundance signatures
- Wider variety of abundances possible compared to dredge-up

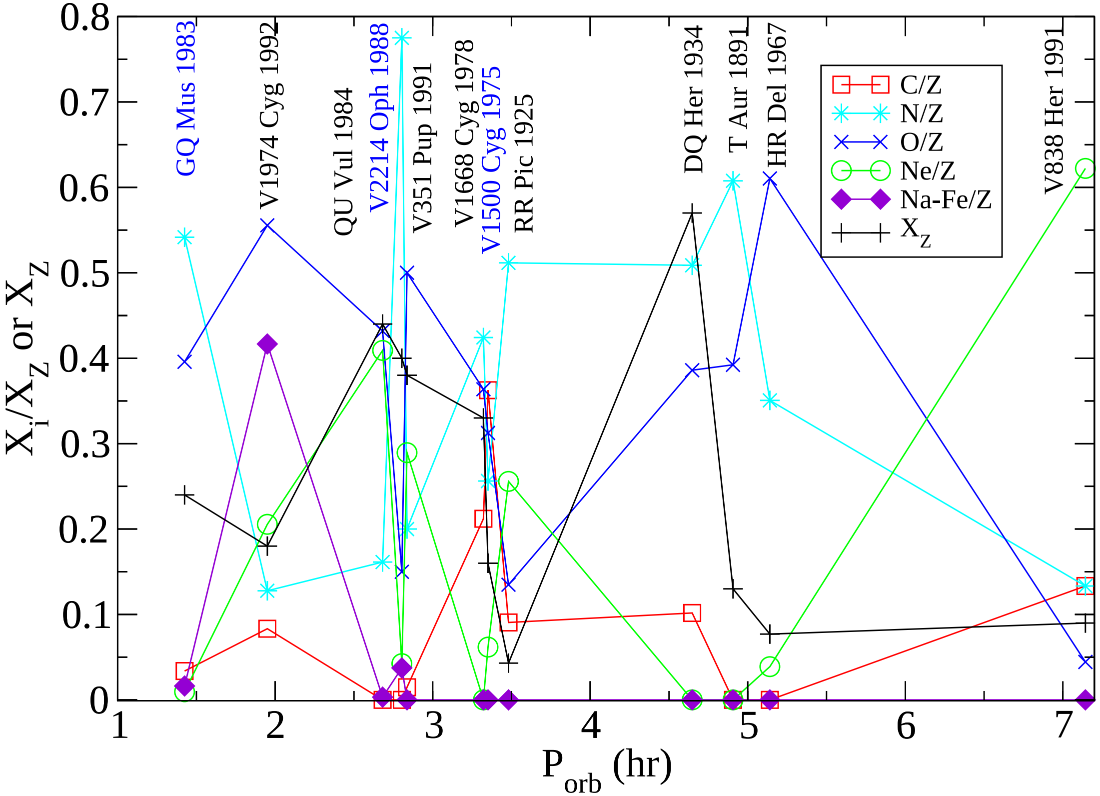


Glasner & Truran 2009, ApJ, 692, L58

$M = 1.35 M_\odot$, $T_c = 4 \times 10^6$ K, $\langle \dot{M} \rangle = 10^{-11} M_\odot$ yr^{-1}

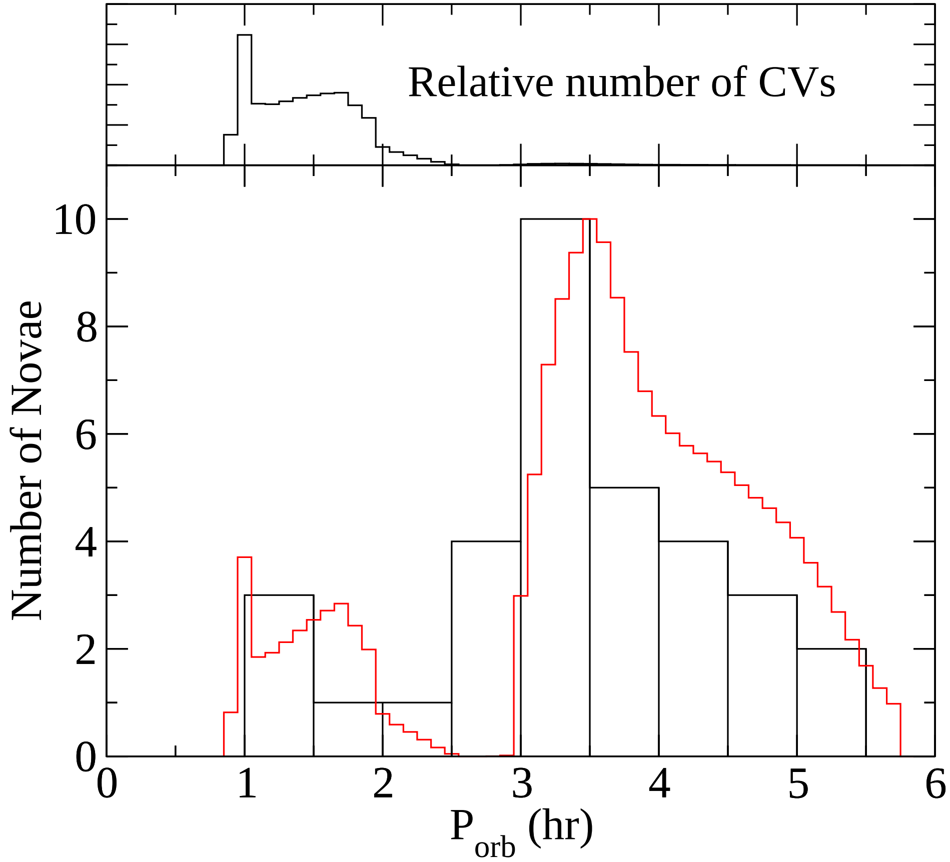
Nova Abundance Patterns

- Heavy element enrichment predominantly $P_{\mathrm{orb}} < 3$ hours
- Wide variation of nova abundances
- Blue are candidate magnetics also have low $\langle \dot{M} \rangle$



compilation Gehrz et al. 1998, PASP, 110, 3

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

- Wind-limited thermal timescale mass transfer form core SN Ia progenitor candidates
- For Novae, CV evolution sets T_c from $\langle \dot{M} \rangle$ – often leaves only M unknown if $P_{\rm orb}$ can be measured.
- Short period and magnetic Novae show distinct nucleosynthesis
- Relative nova rate with orbital period reproduced by canonical interrupted magnetic braking CV scenario

Open Questions

- Can wind-limited accretion provide necessary SN Ia progenitors without introducing bad features?
- Relative role of enrichment from carbon-rich core material before vs. during the Nova runaway
- Mass evolution of primary in Nova systems