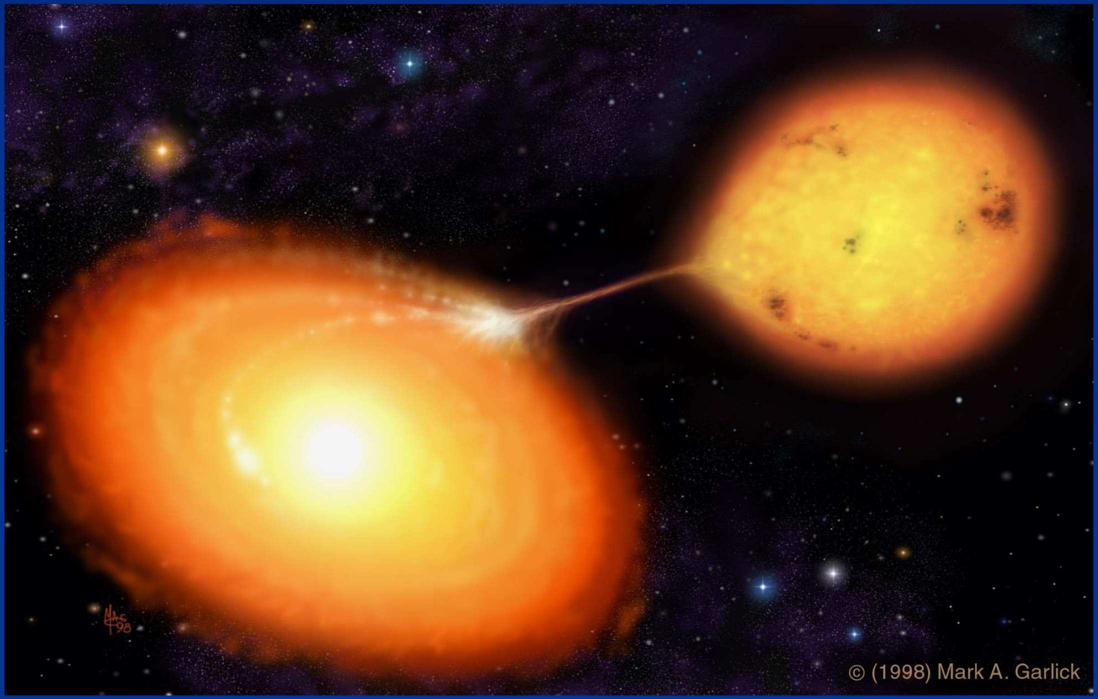
CATACLYSMIC VARIABLES



AND THE TYPE Ia PROGENITOR PROBLEM

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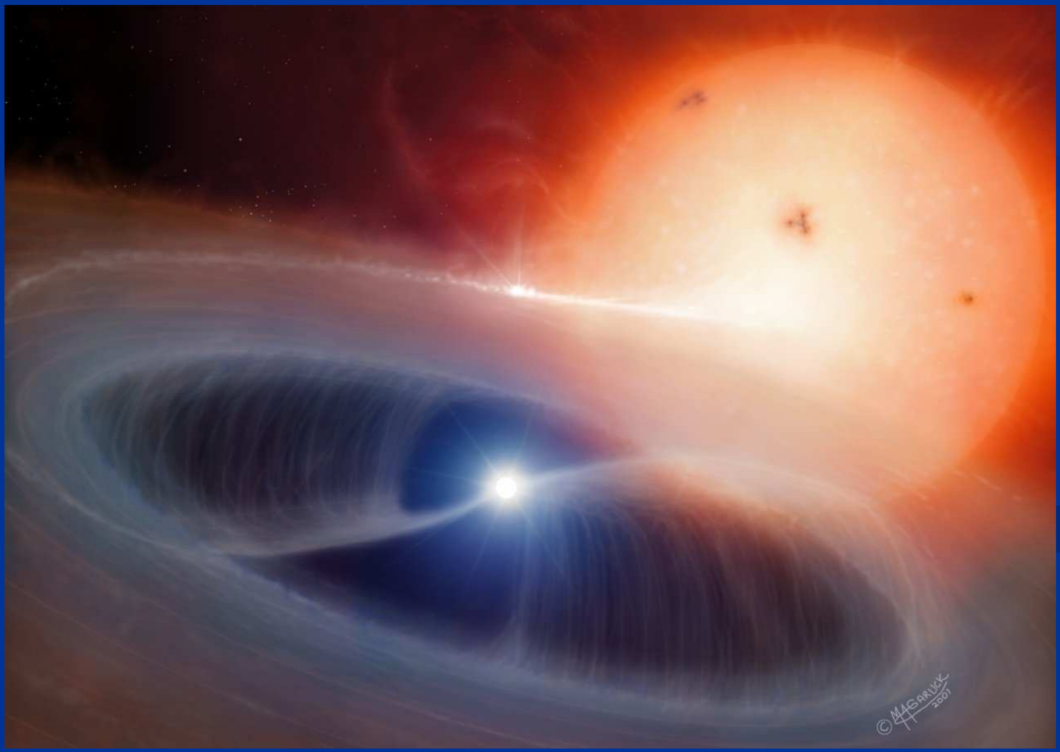
SNOVAE07 Feb. 23, 2007

Cataclysmic Variables

CVs are characterized by a low-mass star/BD (donor) losing mass to an accreting WD. There is a rich variety of “subclasses” (associated with disk or WD)

- Classical Novae
- Dwarf Novae
- SU Ursae Majoris
- Z Camelopardalis
- Recurrent Novae
- Nova-Like
- SW Sextantis
- Polars & Int. Polars
- SuperSoft Sources



Type Ia Progenitors?

Whelan & Iben (1973) first proposed that CVs could be Type Ia progenitors

$M_{wd} > M_{ch} \Rightarrow$ good standard candles

Single Degenerate Channel:

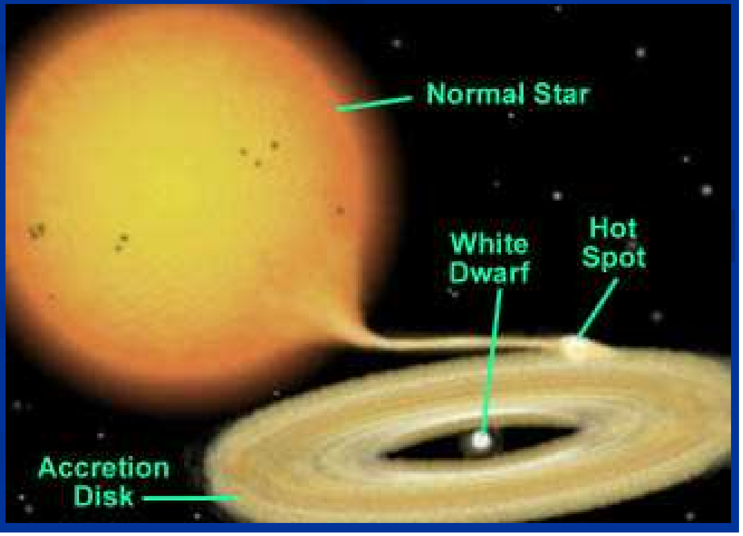
- ☺ Candidate progenitors observed (SSXSs, Symbiotics, CVs)
- ☹ Fine tuning of accretion rate is needed to avoid nova and/or CE (small volume in the phase space)
- ☹ Absence of H in the spectra

Cataclysmic Variables

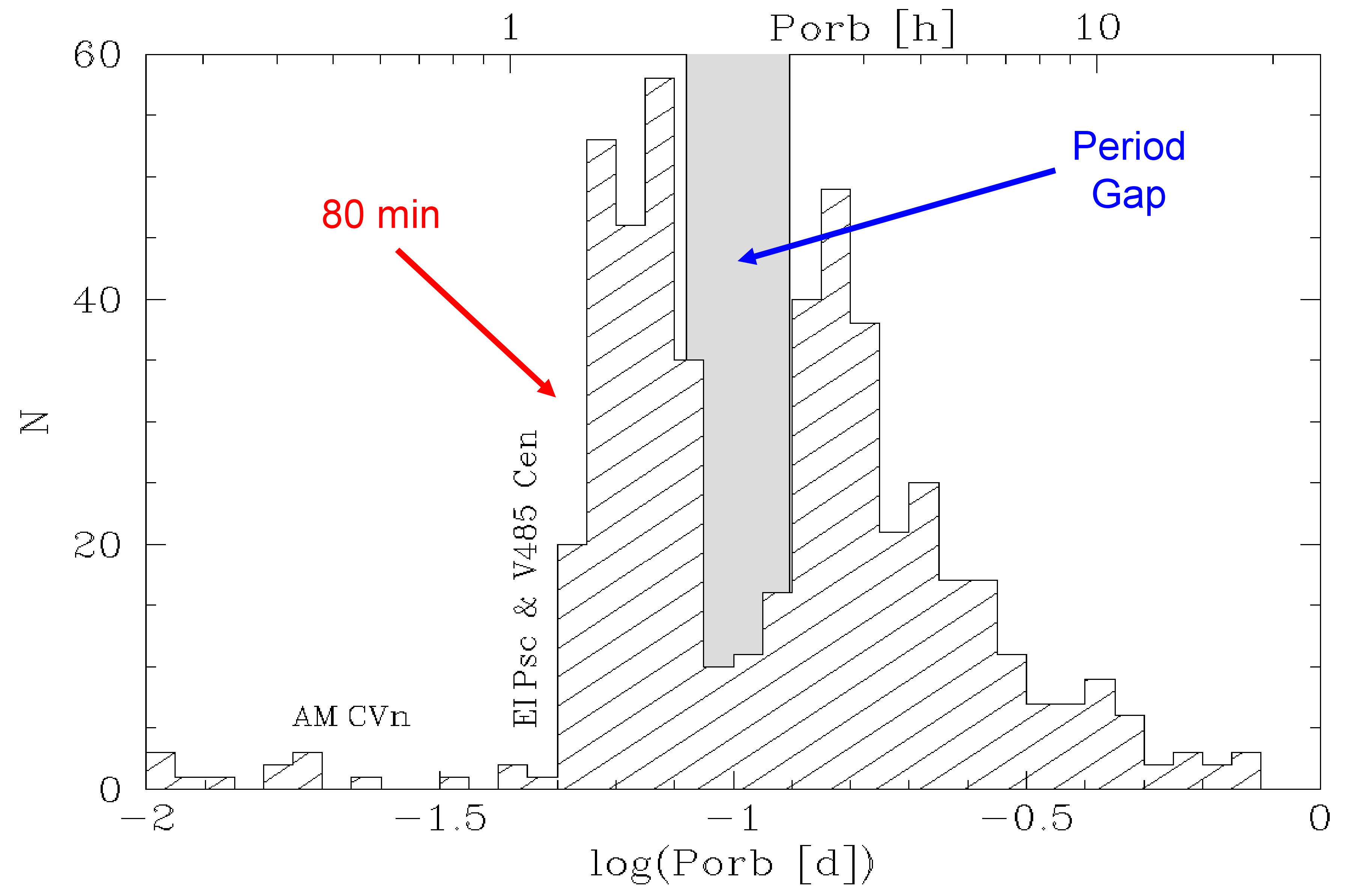
- CVs are semi-detached that transfer mass by RLOF binaries (can be non-conservative)
- CVs have ~70 min < P_{orb} < ~12 hours
- White dwarf masses of ~0.3 to 1.4 $M_{\odot}$
  - ~10-20% are magnetic (10-250 MG).
- Donor (secondary) have masses from ~1.2 to ~0.02 $M_{\odot}$

Any model must be able to explain the salient features:

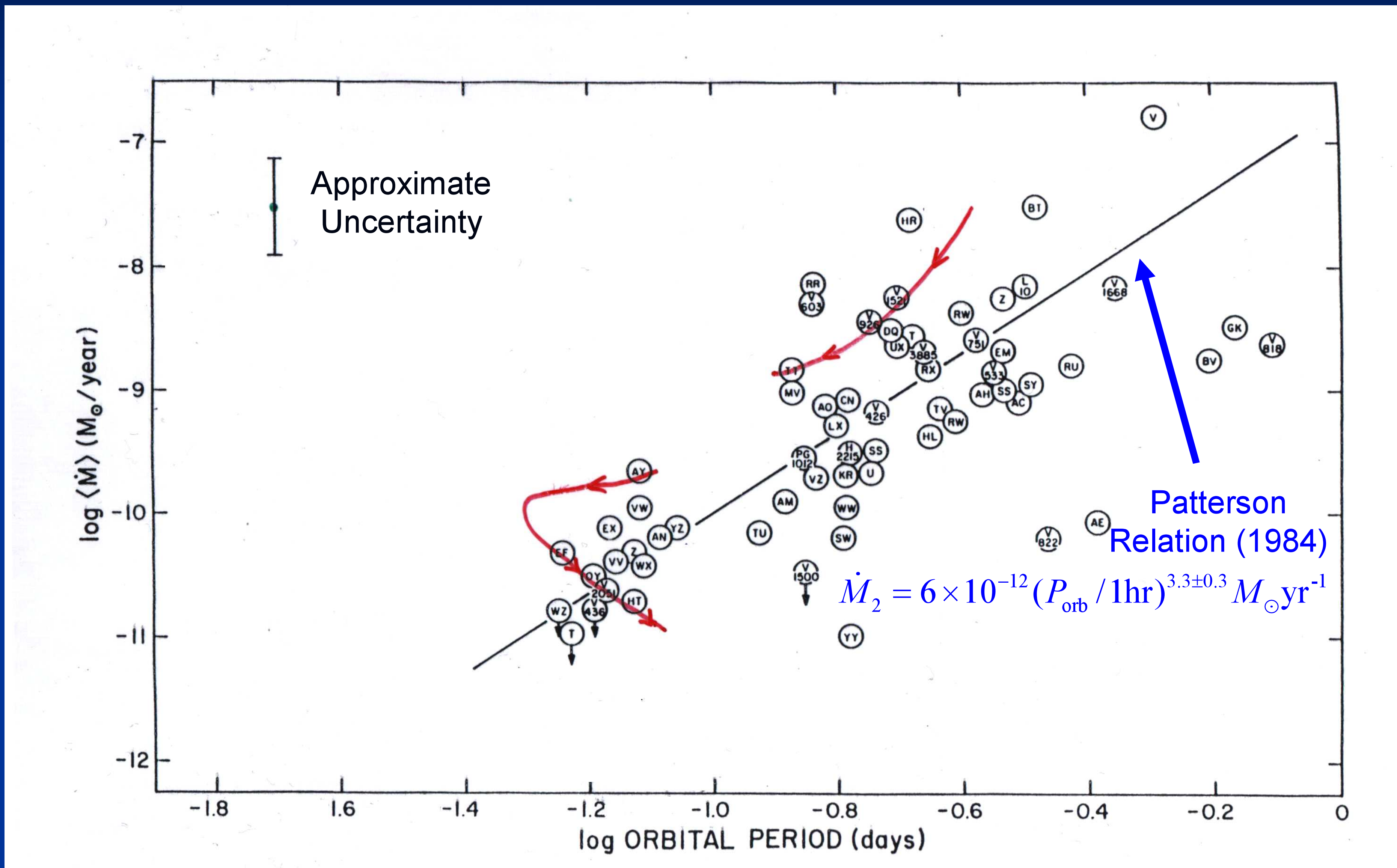
1) Orbital Period Distribution
2) Mass-Transfer Rates
3) Morphology



CV P_{orb} Distribution

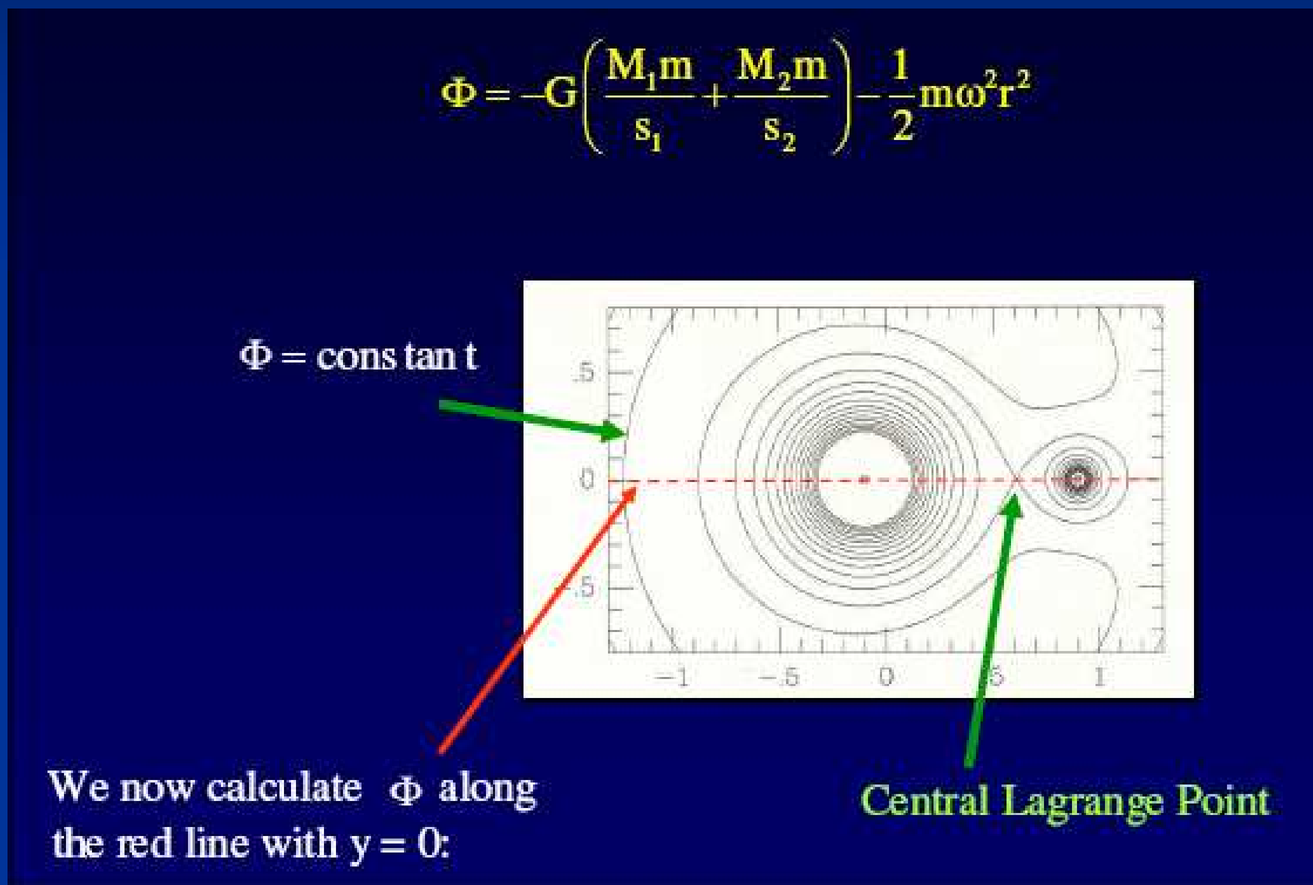


Inferred Mass Transfer Rates



“Standard Model”

The donor overflows its Critical Equipotential



Matter flows through the inner Lagrange point (L_1) from the donor star (M_2) to the compact accretor (M_1). The critical Roche equipotentials intersect the L_1 point.

Drivers of Mass Transfer

- The donor must expand wrt the Roche Lobe (or the RL must shrink)
- CASE 1: Nuclear evolution

$$\tau_{nuc} \simeq 10^{10} \frac{M}{M_\odot} \frac{L_\odot}{L} \text{yr} \approx 10^{10} \left(\frac{M}{M_\odot} \right)^{-2.5} \text{yr}$$

- The donor expands on its nuclear timescale
- Mass transfer can be initiated on SGB or RGB

Drivers of Mass Transfer

- CASE 2: Thermal Timescale Mass Transfer (TTMT)

$$E_{th} = \text{-}0.5 E_{grav} \sim GM^2/R, \text{ so } \tau_{th} \sim GM^2/RL$$

$$\tau_{\mathrm{KH}} \simeq 3.1 \times 10^7 \left(\frac{M}{M_\odot} \right)^2 \frac{R_\odot}{R} \frac{L_\odot}{L} \mathrm{yr} \approx 3.1 \times 10^7 \left(\frac{M}{M_\odot} \right)^{-2} \mathrm{yr}$$

- Donors with radiative envelopes can temporarily shrink due to mass loss, but expand on a KH timescale to re-establish thermal equilibrium

$$\dot{M} \simeq M_{\mathrm{donor}} / \tau_{\mathrm{KH}} \simeq 10^{-6} - 10^{-8} M_\odot \mathrm{yr}^{-1}$$

CASE 3: Angular Momentum Loss (AML)

- Gravitational Radiation

$$\left(\frac{\dot{J}_{\rm GR}}{J}\right) = -1.3\times10^{-8}\left(\frac{M_T}{M_\odot}\right)^{-1/3}\left(\frac{M_1}{M_\odot}\right)\left(\frac{M_2}{M_\odot}\right)\left(\frac{P_{\rm orb}}{1\ \rm hr}\right)^{-8/3}\ \rm yr^{-1}$$

- Magnetic Braking by a MSW (Verbunt-Zwaan Law)

$$\left(\frac{\dot{J}_{MB}}{J}\right) = -7.1\times10^{-6}\left(\frac{M_T}{M_\odot}\right)^{1/3}\left(\frac{M_1}{M_\odot}\right)^{-1}\left(\frac{R}{R_\odot}\right)^{\gamma}\left(\frac{P_{orb}}{1\ \rm hr}\right)^{-10/3}\ \rm yr^{-1}$$

- Systemic Mass Loss $\dot{M}_1 = -\beta\dot{M}_2$ or $\dot{M}_1 + \dot{M}_2 = (1-\beta)\dot{M}_2$

$$\delta J_{\delta M_T} = \delta M_T\ \alpha\left(A^2\omega\right) = (1-\beta)\delta M_2\ \alpha\left(A^2\omega\right)\ ,\ \alpha > 0$$

$$\frac{\dot{J}_{\delta M_T}}{J} = \alpha(1-\beta)\left(\frac{M_T}{M_1}\right)\left(\frac{\dot{M}_2}{M_2}\right)$$

- Total AML: $\frac{\dot{J}_{\rm orb}}{J} = \frac{\dot{J}_{\rm GR}}{J} + \frac{\dot{J}_{\rm MB}}{J} + \frac{\dot{J}_{\delta \rm M_T}}{J} = \frac{\dot{J}_{\rm dis}}{J} + \frac{\dot{J}_{\delta \rm M_T}}{J}$

Binary Dynamics

- From Ed's talk on Friday:

$$\frac{R_L}{A} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1+q^{1/3})} \simeq 0.46\left(\frac{q}{1+q}\right)^{1/3}, \quad q \equiv \frac{M_2}{M_1} \leq 0.8$$

$$\frac{\dot{R}_L}{R_L} \simeq \frac{\dot{A}}{A} + \frac{1}{3}\frac{\dot{M}_2}{M_2} - \frac{1}{3}\frac{\dot{M}_T}{M_T}$$

$$J_{\rm orb} = M_1 M_2 \sqrt{\frac{GA}{M_1+M_2}} \Rightarrow 2\frac{\dot{J}_{\rm orb}}{J} = 2\frac{\dot{M}_2}{M_2} + 2\frac{\dot{M}_1}{M_1} - \frac{\dot{M}_{\rm T}}{M_{\rm T}} + \frac{\dot{\rm A}}{\rm A}$$

$$\frac{\dot{R}_L}{R_L} = 2\frac{\dot{J}_{\rm orb}}{J} - \frac{5}{3}\frac{\dot{M}_2}{M_2} - 2\frac{\dot{M}_1}{M_1} + \frac{2}{3}\frac{\dot{M}_{\rm T}}{M_{\rm T}}$$

Rate of Mass Transfer

$$\frac{\dot{R}_L}{R_L} = -\frac{\dot{M}_2}{M_2}\left(\frac{5}{3} - 2\beta q - \frac{2}{3}(1-\beta)\frac{q}{1+q}\right) + 2\frac{\dot{J}_{\rm dis}}{J} - 2\alpha(1-\beta)(1+q)\left(-\frac{\dot{M}_2}{M_2}\right)$$

↑ internal J redistribution <0 **OR** >0

↑ dissipation <0

↑ systemic J loss <0

If the system remains in contact $\Rightarrow$ $R_L(t) = R_2(t)$

$$\frac{\dot{R}_L}{R_L} = \frac{\dot{R}_2}{R_2} \simeq \xi_{ad}\frac{\dot{M}_2}{M_2} + \frac{\dot{R}_{2,nuc}}{R_2} + \frac{\dot{R}_{2,th}}{R_2}$$

where

$$\xi_{ad} \equiv \left[\frac{d\ln(R)}{d\ln(M)}\right]_{ad}$$

The equations describing the mass-transfer can be approximated as follows:

$$-\frac{\dot{M}_2}{M_2} \simeq \frac{\dot{R}_{2,nuc}/R_2 + \dot{R}_{2,th}/R_2 - 2\dot{J}_{\rm dis}/J}{D(\alpha,\beta,q,\xi_{ad})}$$

Dynamical Instability

Mass transfer is ONLY stable if numerator and denominator > 0

N.B.: If D < 0 then the binary system is dynamically unstable

$\Rightarrow$ CE phase/merger

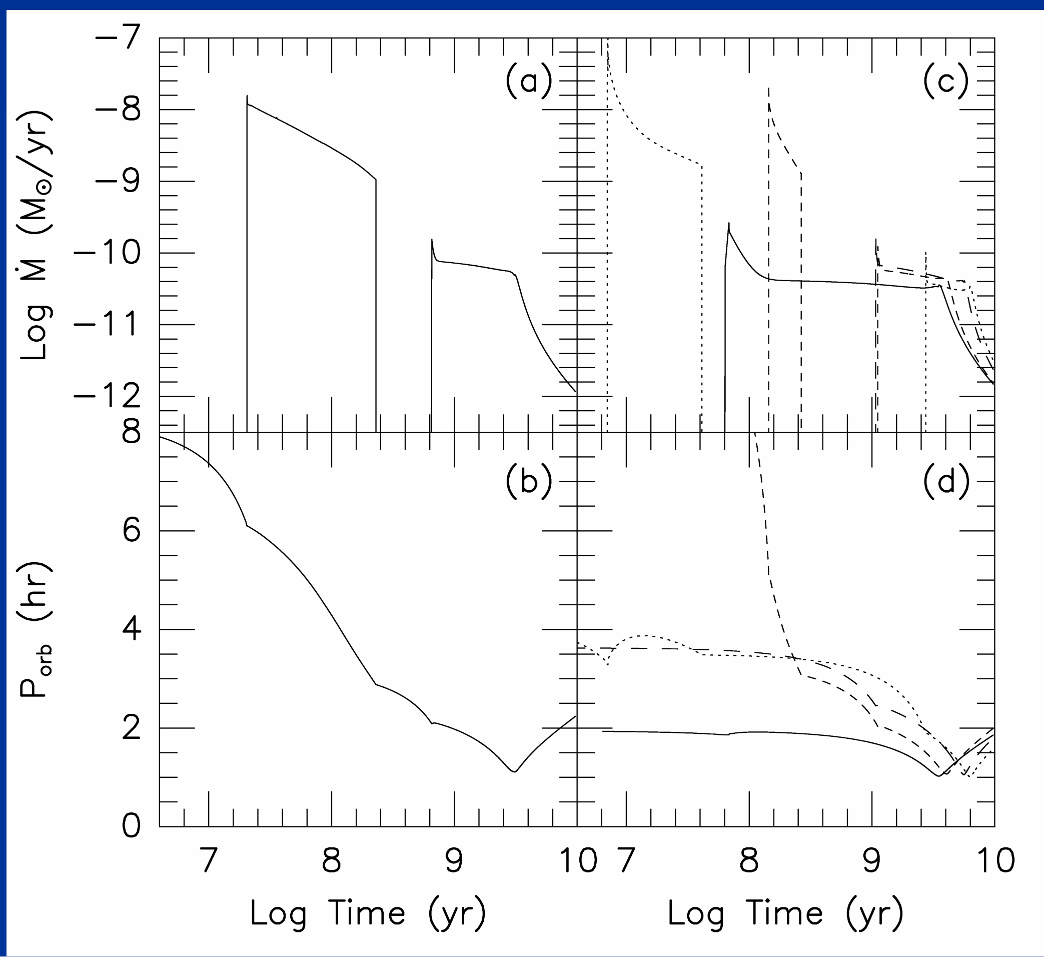
$$D(q,\alpha,\beta,\xi_{ad}) = \left[\frac{5}{3} + \xi_{ad} - 2\beta q - \frac{2q(1-\beta)}{3(1+q)} - 2\alpha(1-\beta)(1+q) \right]$$

Sign of *D* very much depends on the value of α

Importance wrt Type Ia SNe was noted by Di Stefano, Nelson, Rappaport, Lee and Wood (1995); Han and Podsiadlowski (2004)

Binary Evolution

- Assumptions: 1) donor unevolved; 2) Mass lost from the system due to CNe; 3) Interrupted mag. braking



Howell, Nelson & Rappaport (2001)

Orbital Period Gap

- Assumptions: 1) MB severely attenuated when donor becomes fully convective (IMB); 2) Mass lost from the system due to CNe

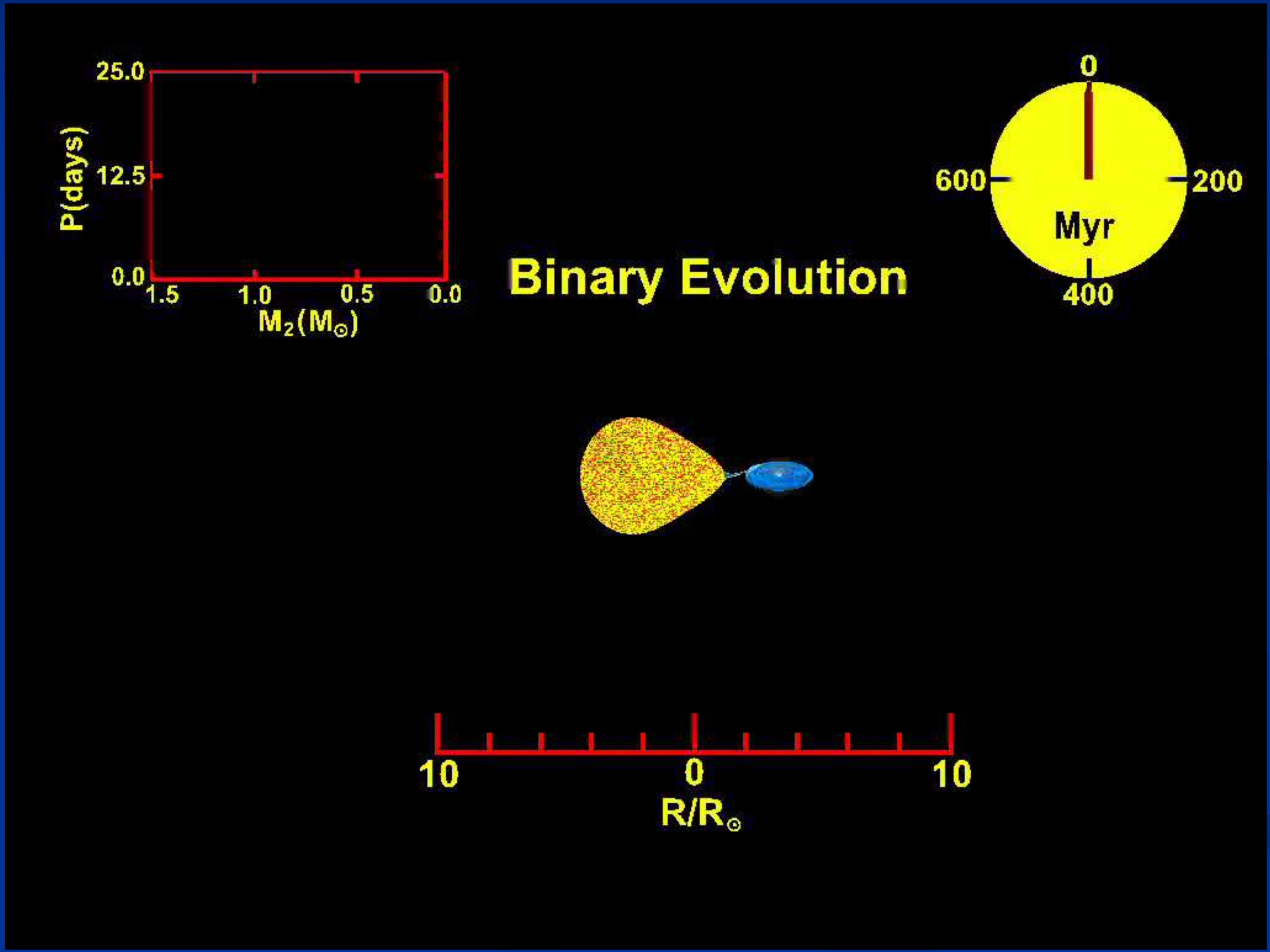
Let f represent a thermal 'bloating factor': $R_2 = faM_2^b$

Roche Geometry Constraint:

$$f = \left(\frac{P_{upper}}{P_{lower}} \right)^{2/3} \sim 1.2 - 1.3 \Rightarrow \text{thermally evolving}$$

EVOLVED DONORS

Initial Conditions: $M_{wd} = 1.0\ M_{\odot}$ $M_{donor} = 1.5\ M_{\odot}$



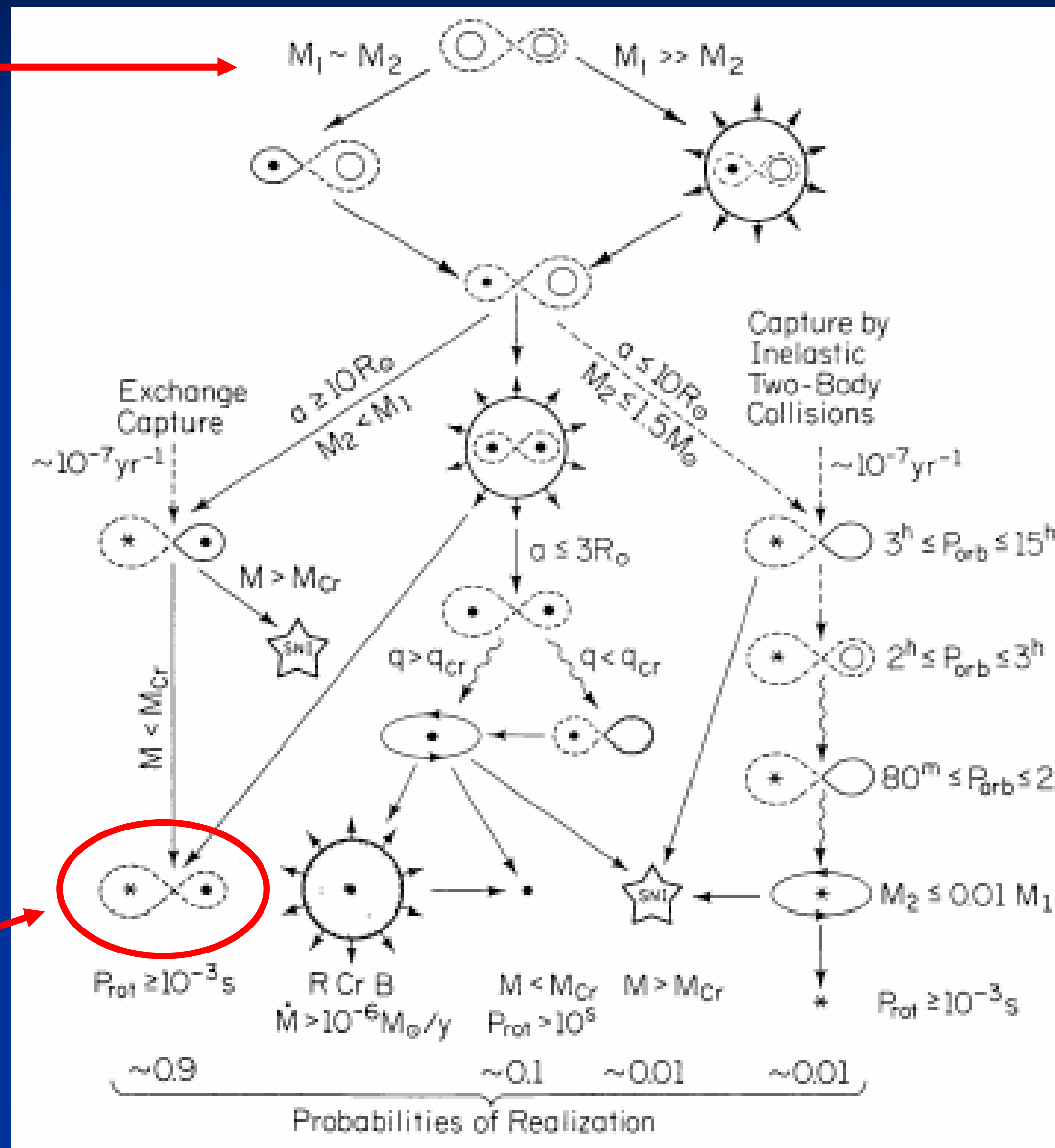
A sharp bifurcation in P_{orb} is possible.

Formation of CVs

Start with primordial binary

Iben & Tutukov (1991)

Yungelson (2005)



CV Sequence

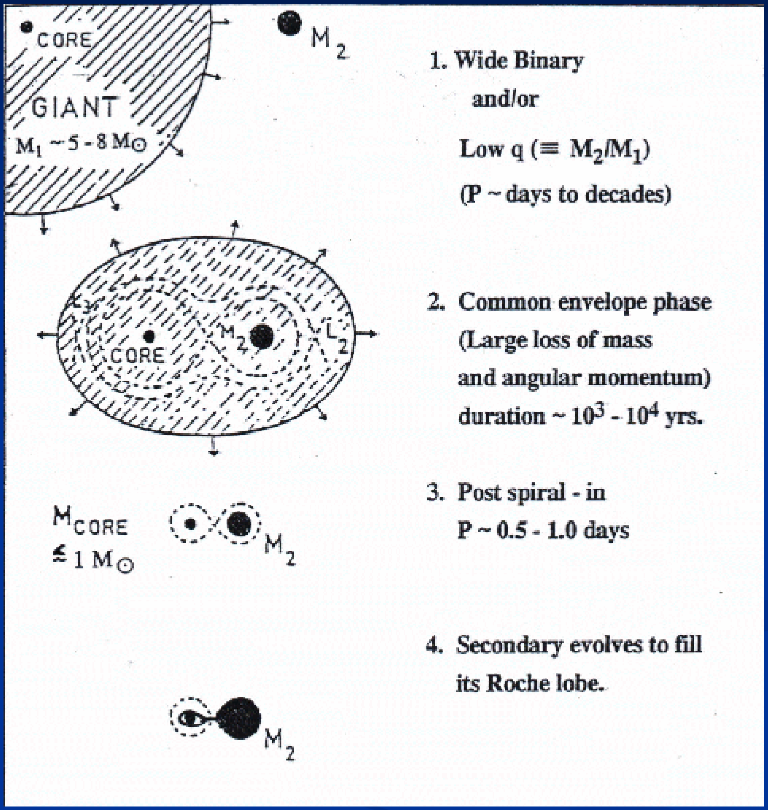
Most Probable End State

CE Evolution

Webbink (1984)

de Kool (1990)

Taam & Sandquist (1998)



Based on a 'first principles' energy argument:

$$\alpha_{\rm CE} \frac{GM_2}{2}\left(\frac{M_{\rm core}}{a_f} - \frac{M_1}{a_i}\right) = \frac{GM_{\rm env}\left(M_{\rm env} + 3M_{\rm core}\right)}{R_1}$$

$\alpha_{\rm CE}$ is the efficiency of the deposition of E in removing the CE

Population Synthesis

Derive the properties of CVs (and other IBs) in the present epoch given their formation throughout the history of the Galaxy.

Initial Distribution → Final Distribution

$n_0(M_{10}, M_{20}, P_0)\, dM_{10}\, dM_{20}\, dP_0 \longrightarrow n_f(M_{1f}, M_{2f}, P_f)\, dM_{1f}\, dM_{2f}\, dP_f$

Population Synthesis

1) Efficiency of CE process
   - Separation of orbit

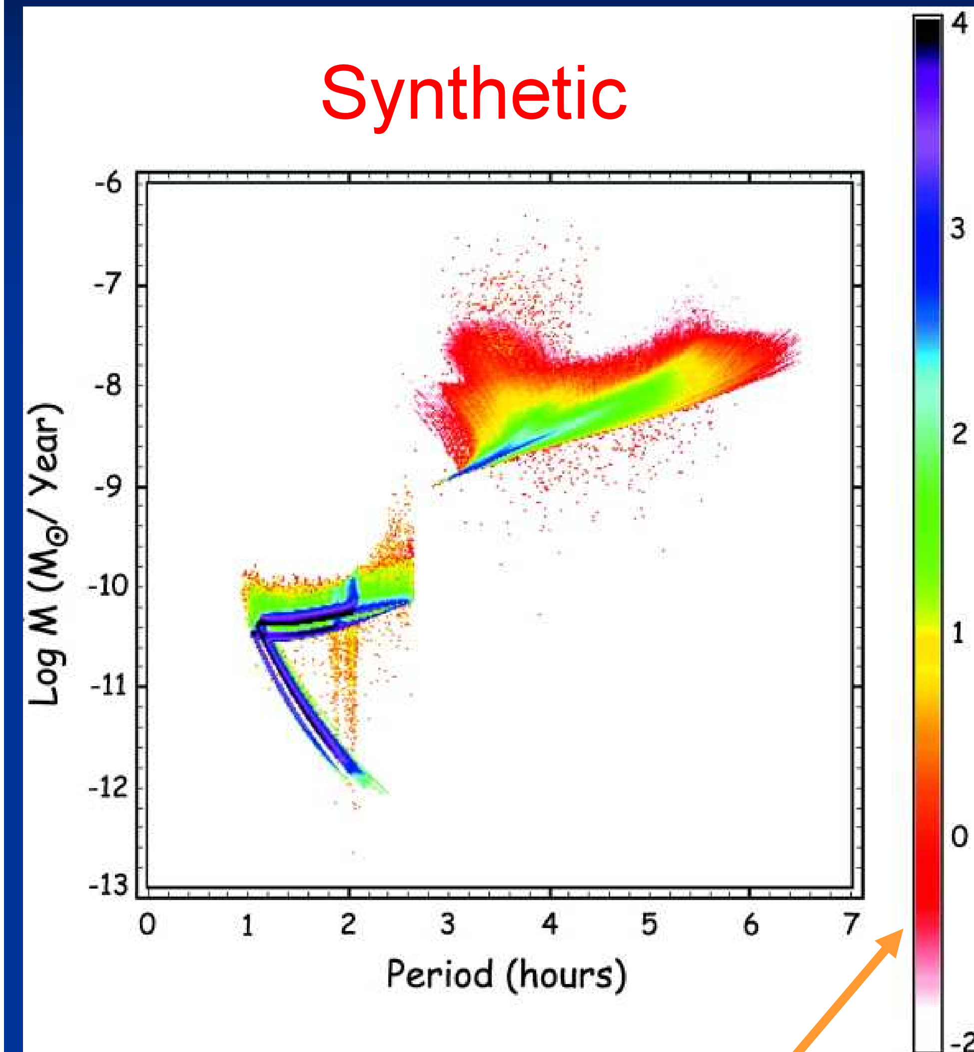
2) Choice of initial mass of primary

3) Correlation of masses

4) Birth rate function (BRF)

Large number of uncertainties!

Models of the Current Paradigm

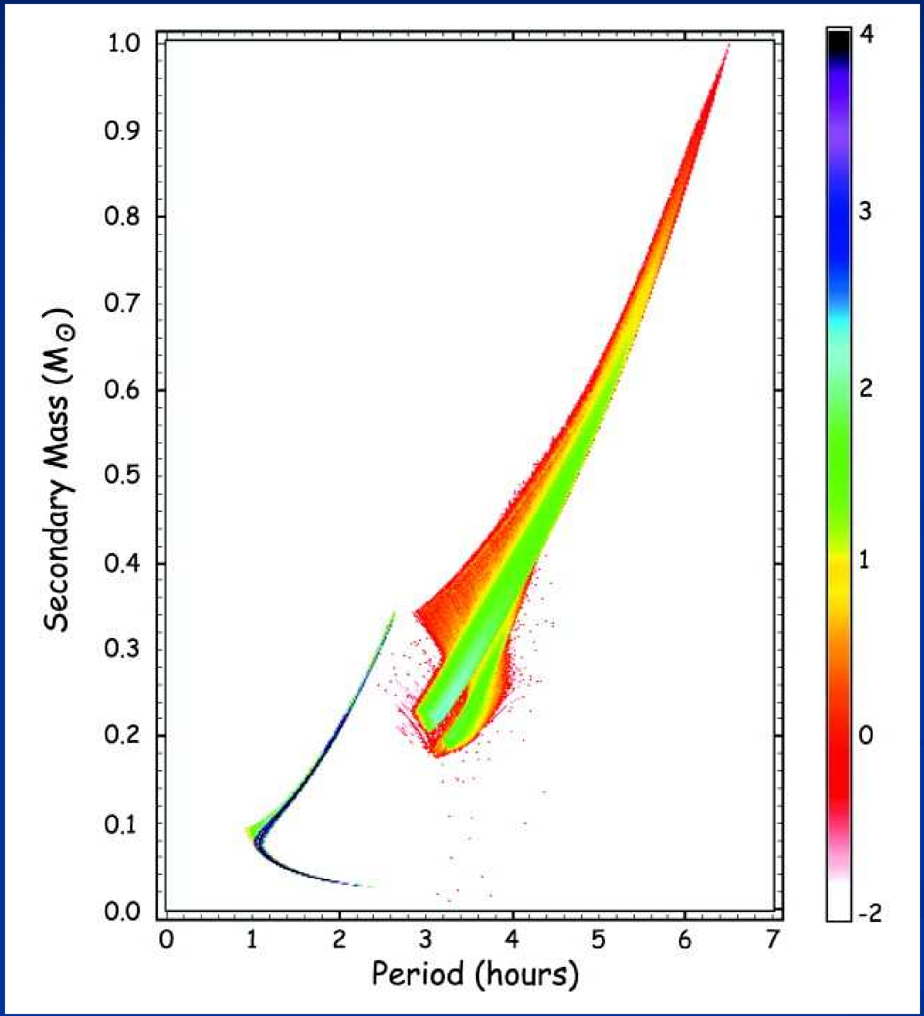


Relative Logarithmic Probability

Evolution of 10 million model CVs. This model represents the present-day population of CVs in the Milky Way assuming an age of 10 GYr.

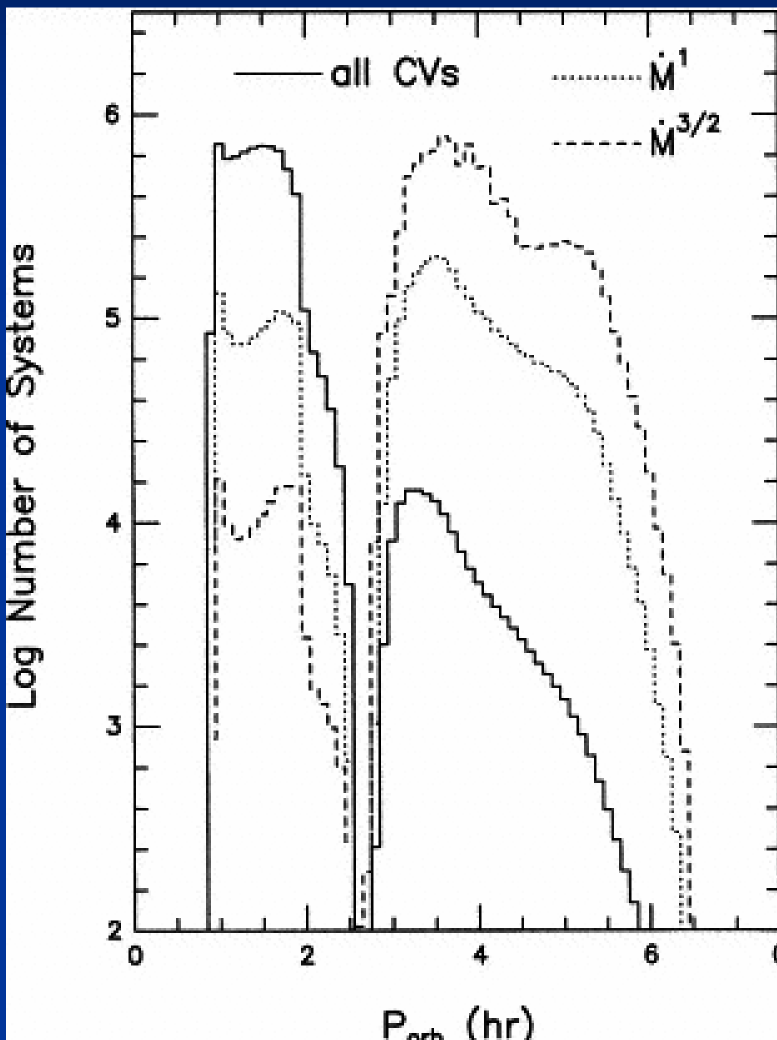
Major Predictions:
1) > 95% of all CVs have short orbital periods (<2 hr).
2) Donors immediately above the period gap are ~25% less massive than would be inferred if the donor was on the MS.

Mass versus P_{orb}



Relative Logarithmic Probability

Cumulative Distribution of CVs



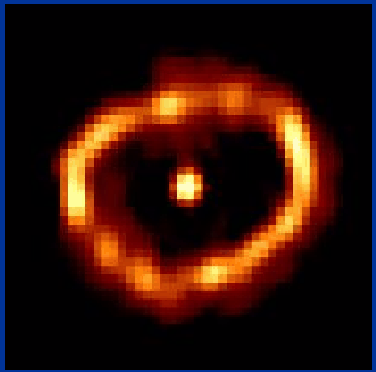
Synthesized distribution matches observed one reasonably well (once selection effects are accounted for).

Caveats: 1) P_{min} theoretical is < 80 min
2) Expect more CVs near P_{min} ("spike")
3) ~10 times more novae above "gap" (factor of ~100 discrepancy?)

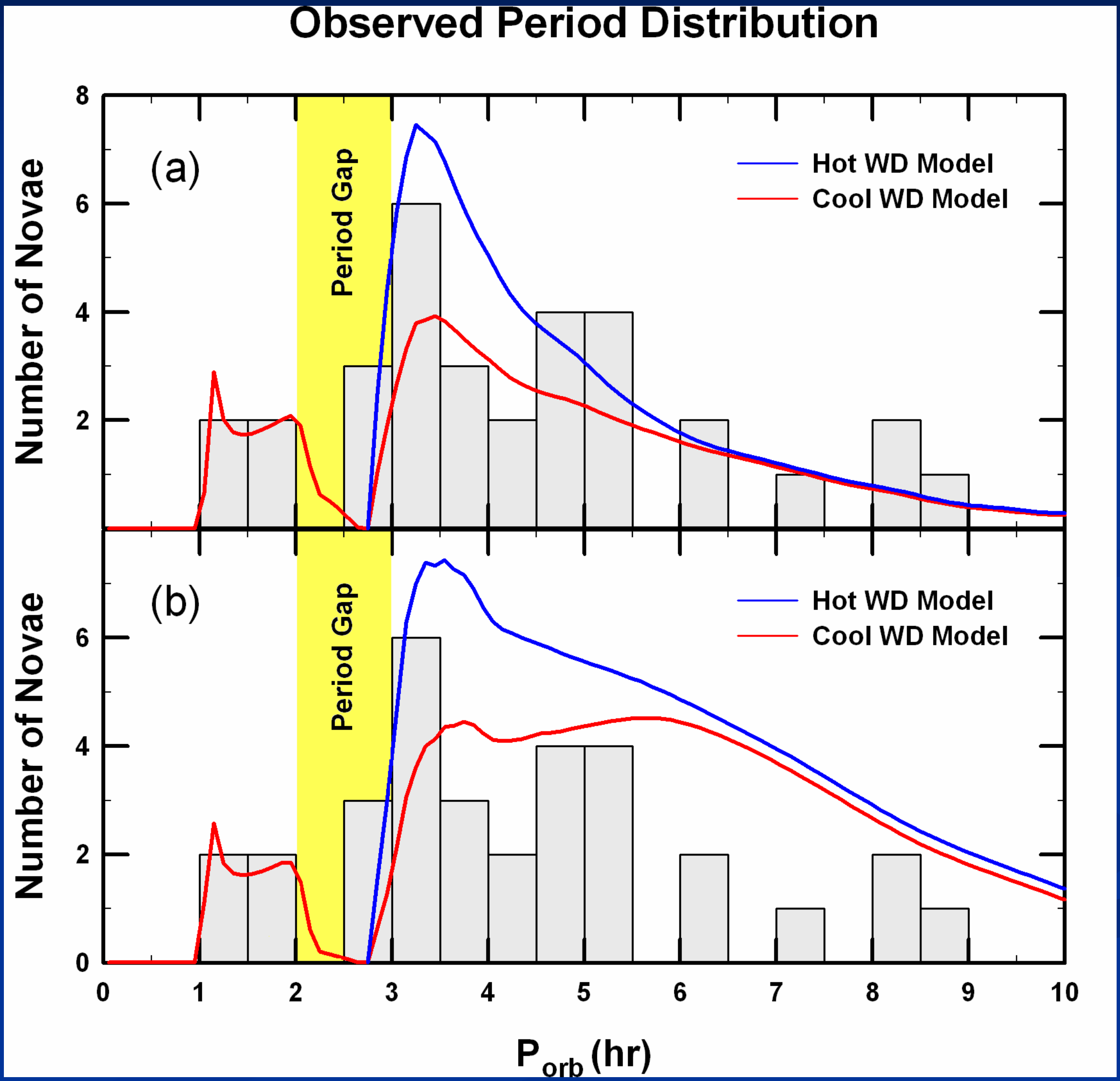
Population Synthesis of CNe

Nelson 2002
Nelson et al. 2004

Pop. Synthesis yields a rate of ~10 – 100 CNe/yr in our Galaxy

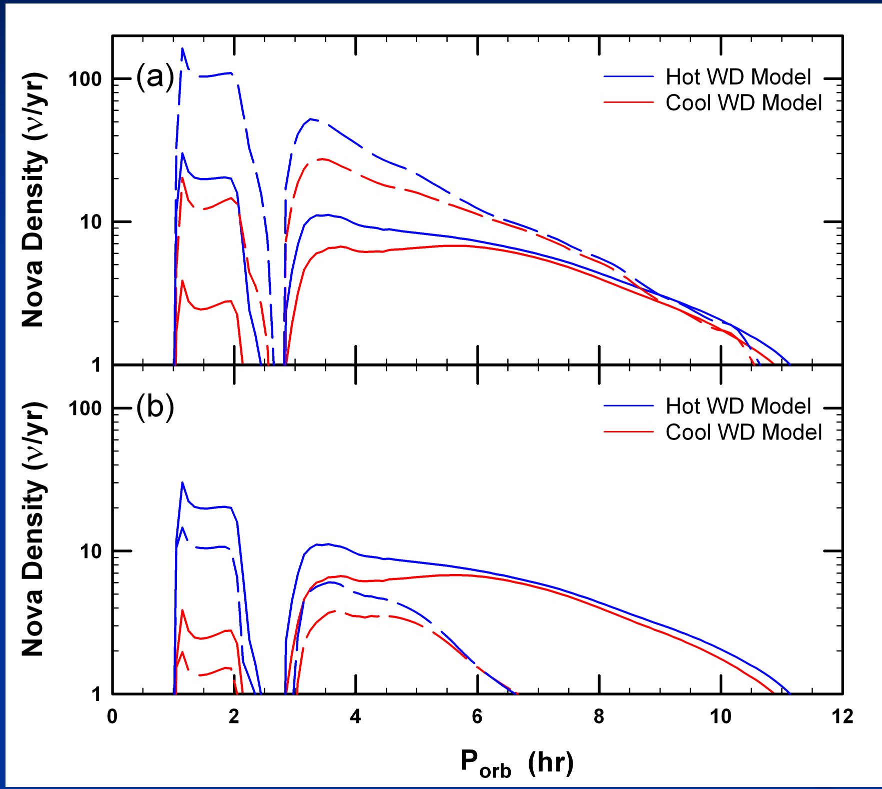


Nova Cygni 1992



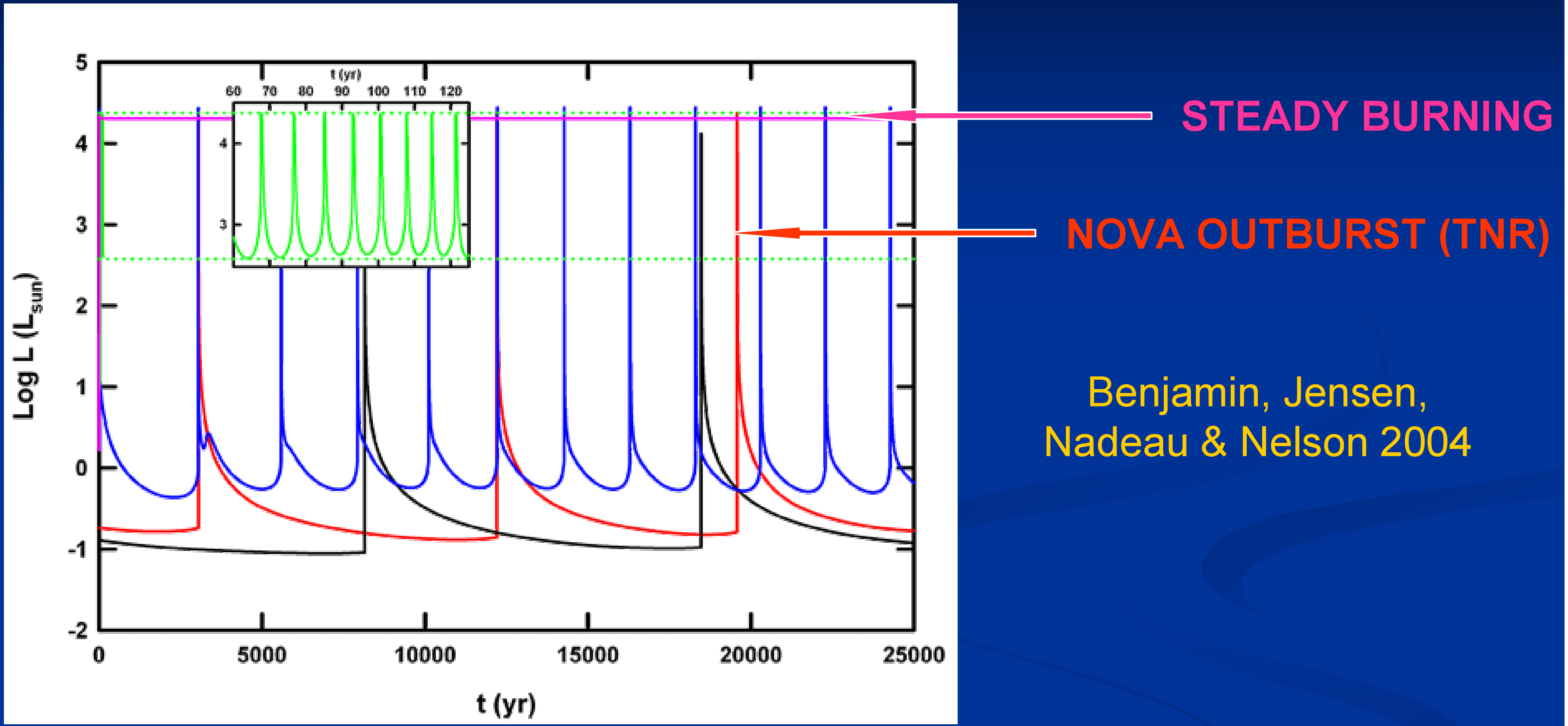
see also Townsley & Bildsten 2004

Galactic Frequencies



Theoretically predicted nova frequencies (densities expressed per hour of orbital period). Case (a): solid lines correspond to $q^{1/4}$ and dashed lines to q^0 (α = 0.3 for both sets of curves). Case (b): solid lines correspond to $\alpha = 0.3$ and dashed lines to $\alpha = 1$ ($q^{1/4}$ for both sets of curves). As in Figure 1, the blue curves correspond to hot WD's and the red curves to cool ones.

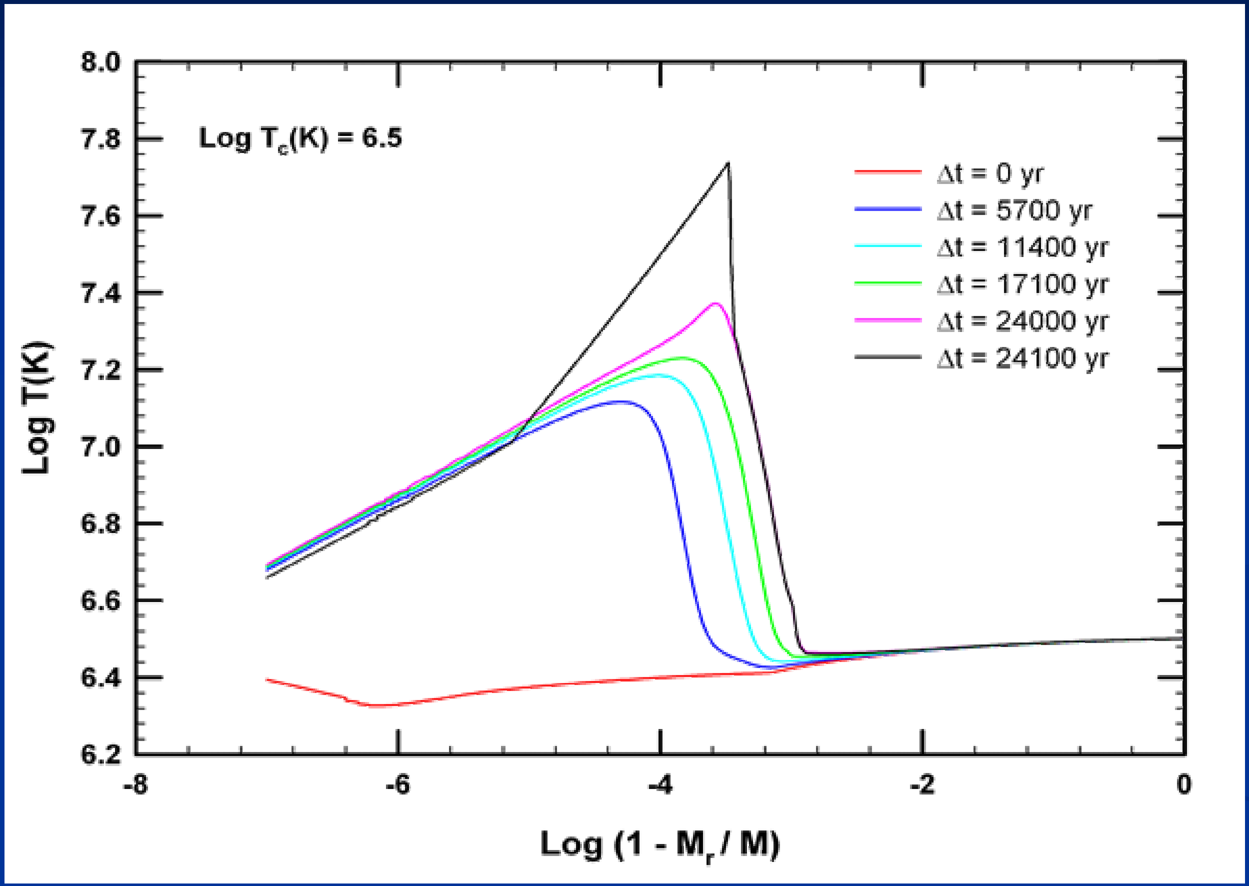
The Transition to Steady Burning



Benjamin, Jensen, Nadeau & Nelson 2004

Mass transfer rate of 1×10^{-9} $M_\odot$ yr^{-1}: (i) **Black curve:** $M_{WD} = 0.95$ $M_\odot$; (ii) **Red curve:** $M_{WD} = 1.0$ $M_\odot$; (iii) **Blue curve:** $M_{WD} = 1.1$ $M_\odot$. Setting $M_{WD} = 1.0$ $M_\odot$, and increasing $\dot{M}$ yields the following: (iv) **Green curve:** 6×10^{-8} $M_\odot$ yr^{-1}; (v) **Pink curve:** 5×10^{-7} $M_\odot$ yr^{-1}. The inset shows the evolution of case (iv) on an appropriately short time scale.

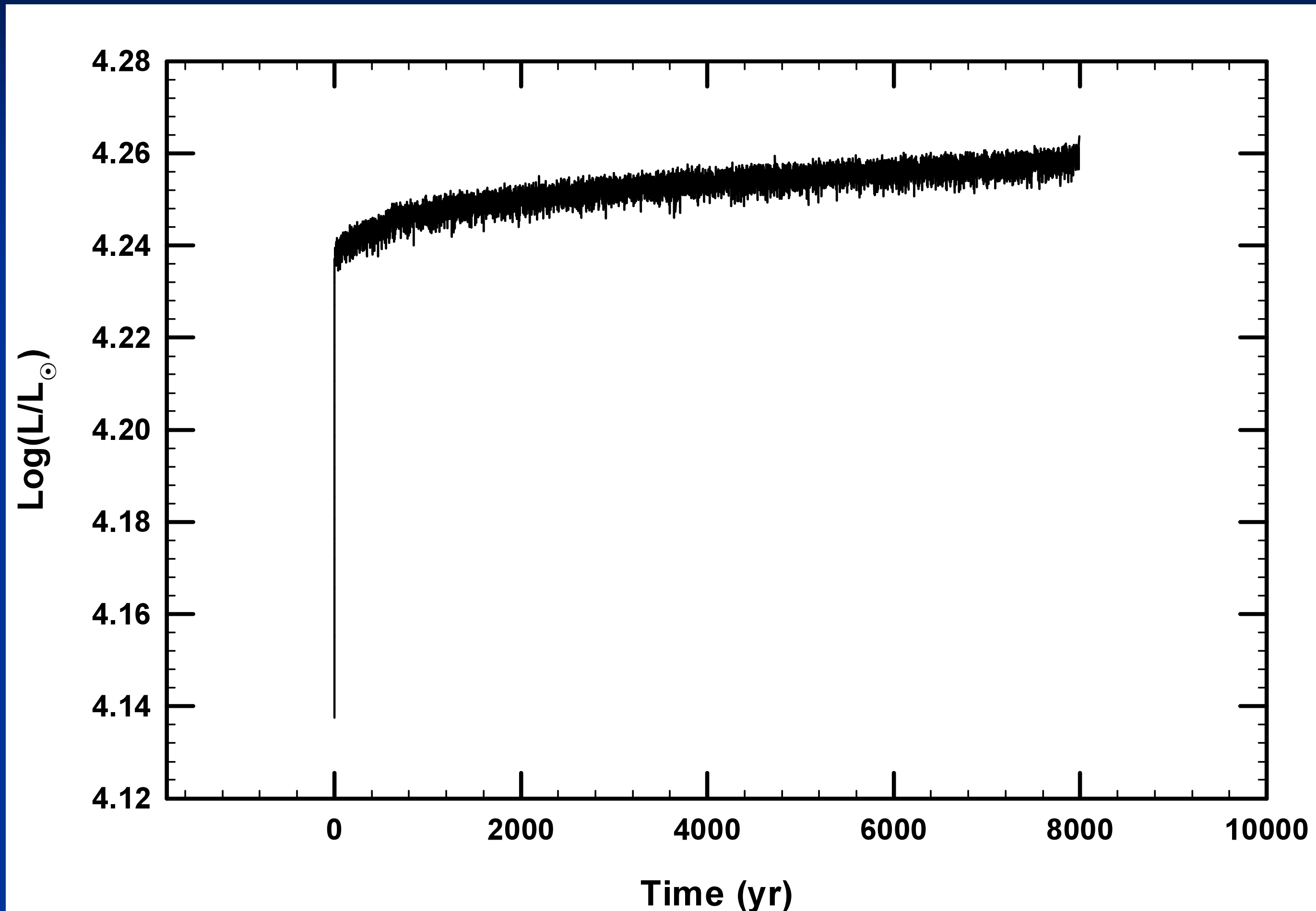
Profile of a Thermonuclear Runaway



Nelson 2005

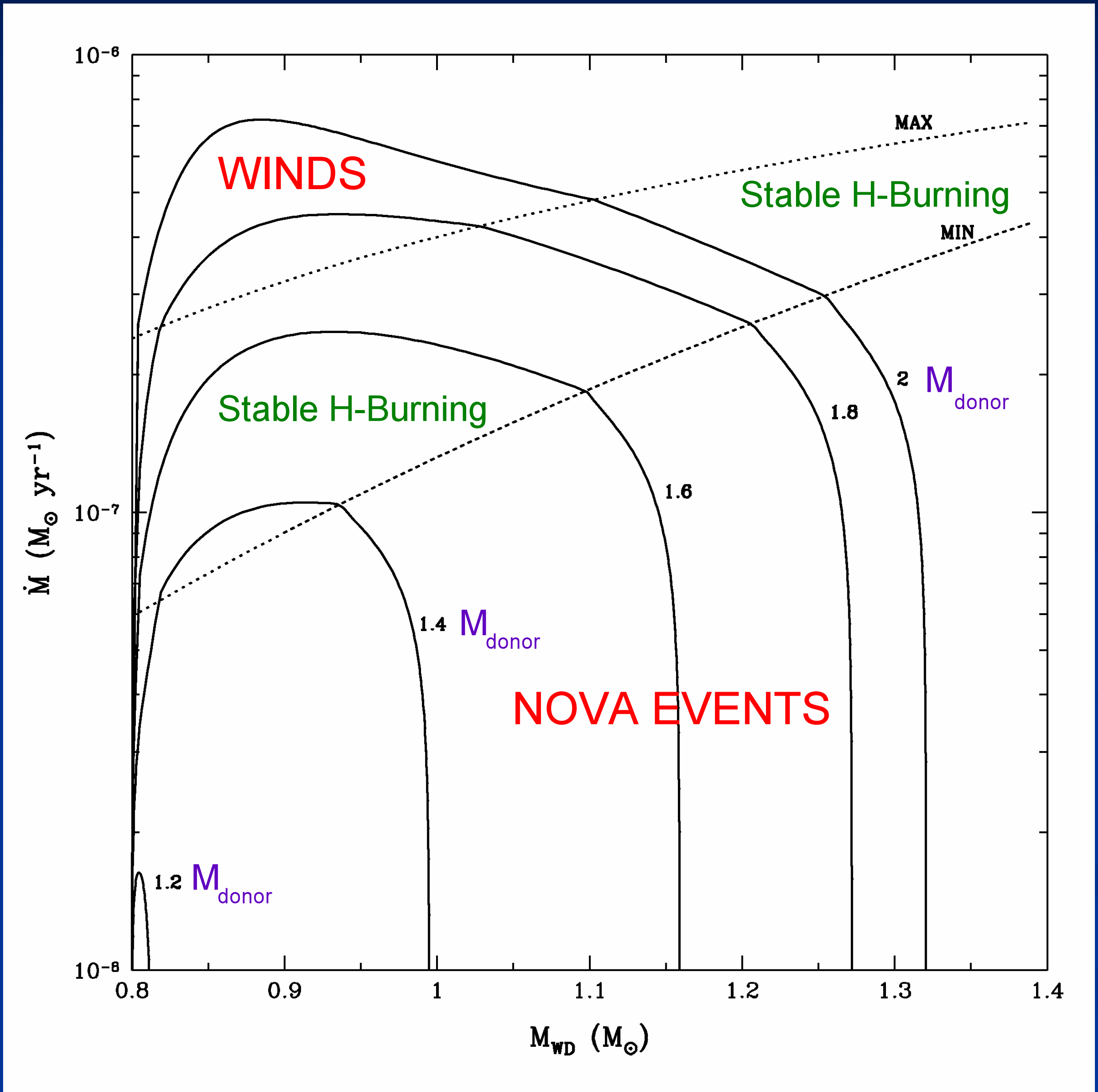
Thermal profile of a 0.7 $M_\odot$ CO WD undergoing accretion at $1\text{x}10^{-8}$ $M_\odot$ yr^{-1}. Each curve corresponds to an evolutionary time (Δt) measured relative to the first model in the sequence. Log T(K) is plotted against the log of the mass fraction (as measured from the surface).

Quasi-Steady Burning



Temporal evolution of the luminosity of an accreting 1.0 $M_{\odot}$ CO WD undergoing accretion at 5×10^{-7} $M_{\odot}$ yr^{-1}. The WD quickly attains a state of quasi-steady H-burning.

Temporal Evolution of Supersofts

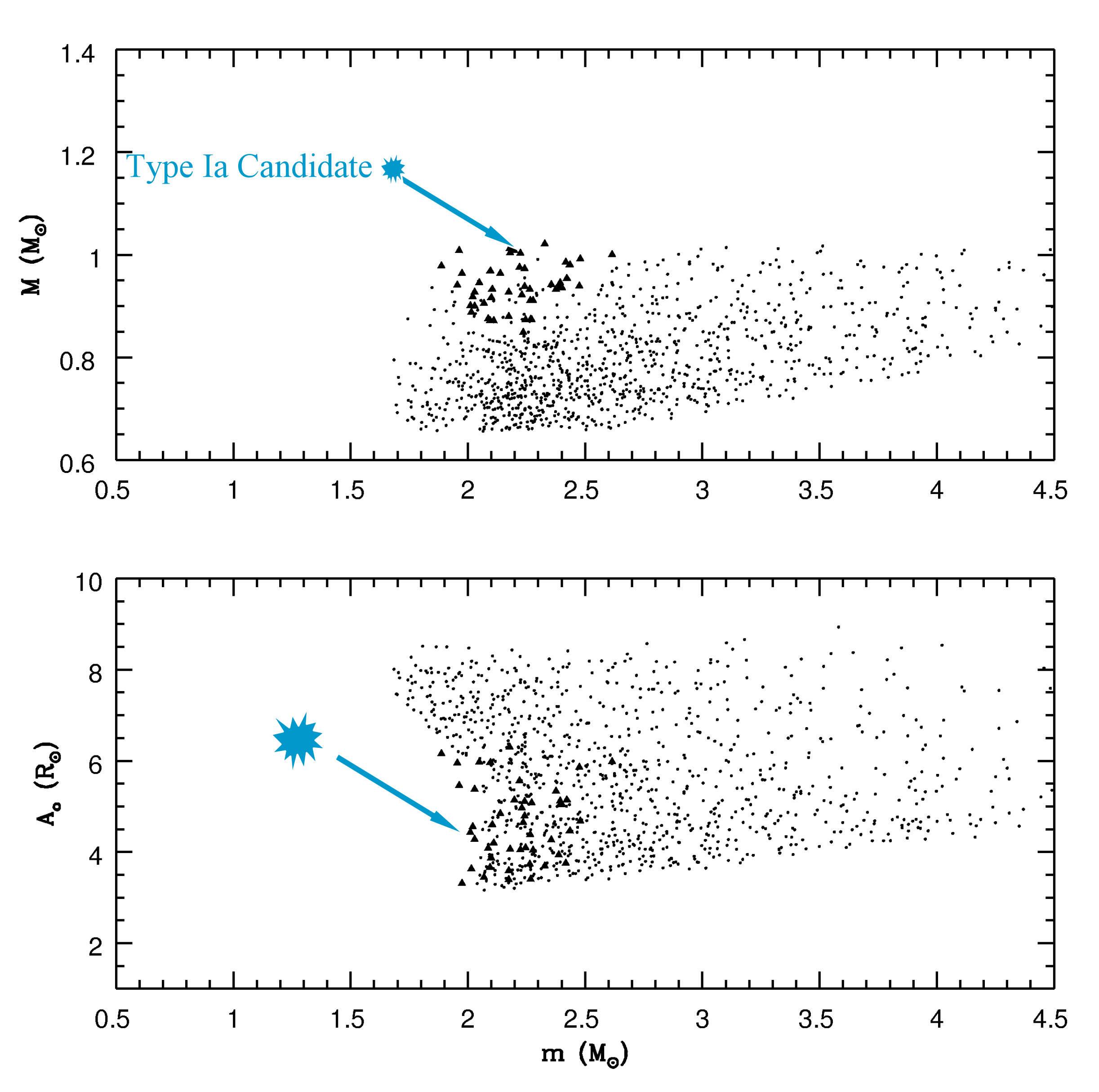


SSXSs can be regarded as "Super CVs"

Van den Heuvel et al. (1991) developed the model of steady H burning on the surface of WDs

Di Stefano & Nelson 1996

Type Ia Progenitors



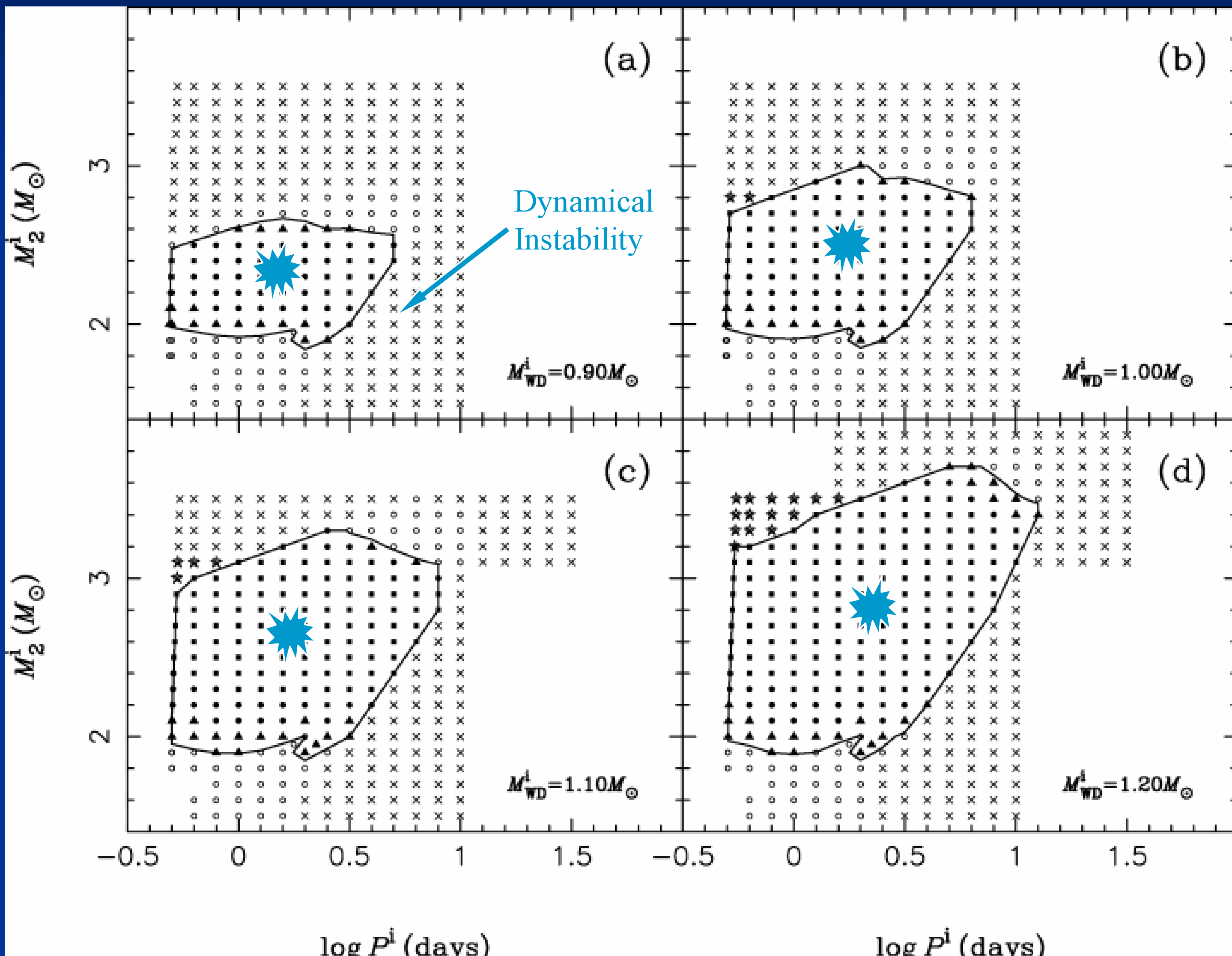
Di Stefano et al. 1995

Synthesis produced a “Type Ia” frequency that was too small by a factor of ~20

The observationally inferred SN Ia rate is ~0.3 century^{-1}

Recent Progenitor Results

Grid of Initial Properties (Parameter Space)



Han and Podsiadlowski 2004

Synthesis produced a Type Ia frequency that was <u>too small by a factor of ~3</u>