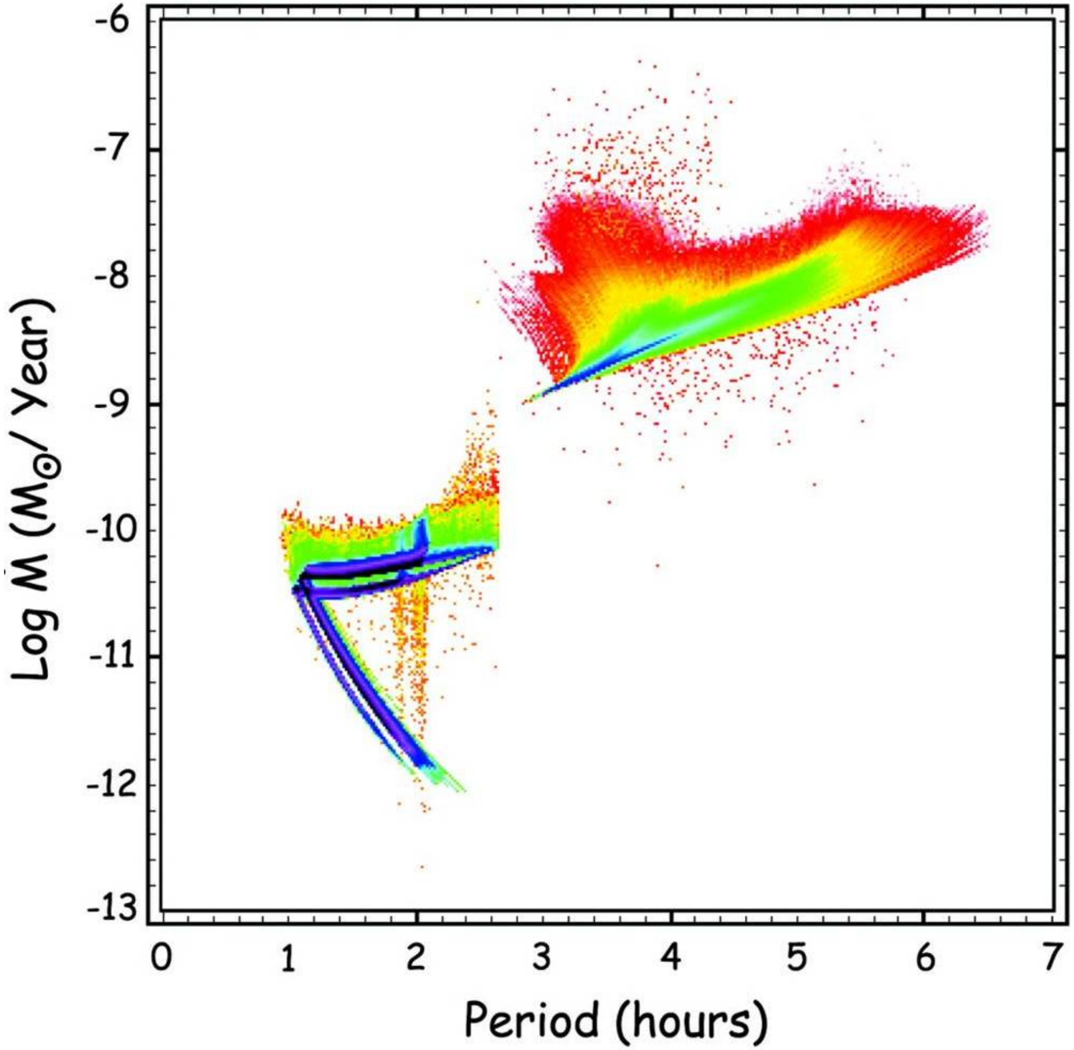
Birthrates and Populations of Cataclysmic Variables



Howell et al. 2001

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Outline

- Introduction

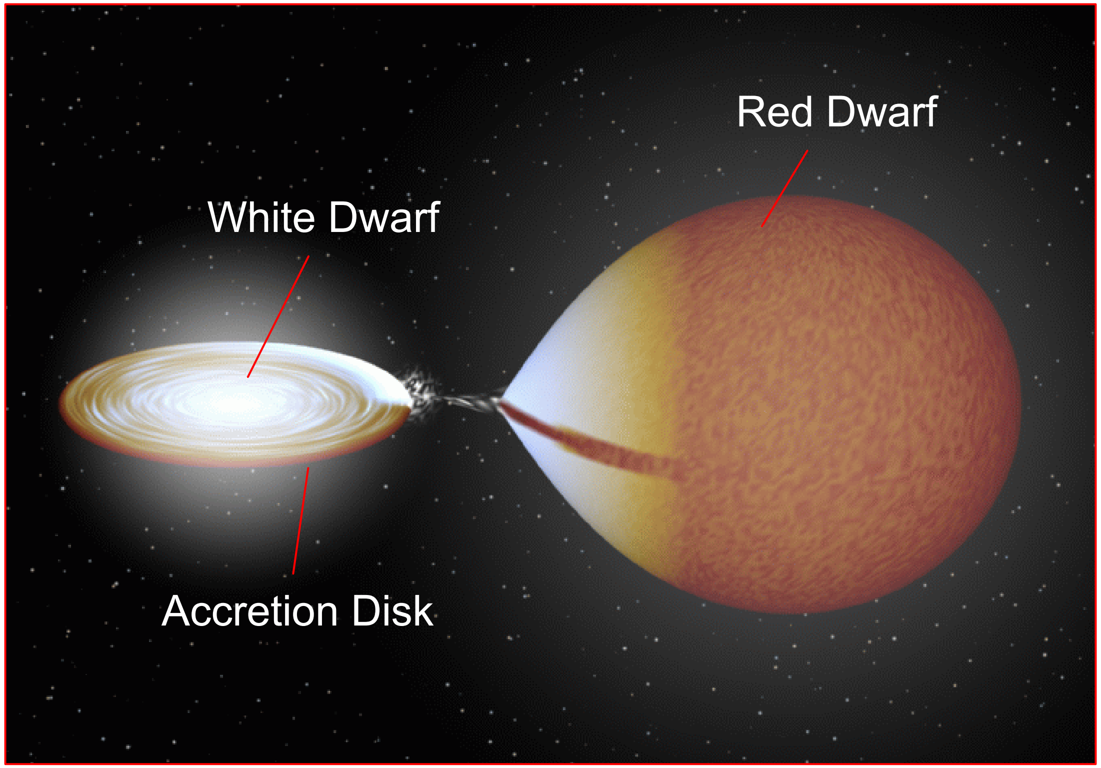
- **Birthrates:** *CV Formation* [30%]
  - The common envelope phase

- **Populations:** *CV Evolution* [60%]
  - Disrupted magnetic braking

- **Deathrates:** *CV Destruction* [10%]
  - Are CVs viable SN Ia progenitors?

- Summary and Conclusions

Introduction: Cataclysmic Variables



Credit: Rob Hynes

- White dwarf primary
- Low-mass MS secondary
- Roche-lobe overflow
- Accretion usually via a disk
- 75 mins < P_{orb} < 12 hrs
- Mass transfer and evolution driven by angular momentum losses
- Nova eruptions every ~10,000 years

Part I: The Formation of Cataclysmic Variables

The Common Envelope Phase

- The need for a CE phase
  - A typical CV may start mass transfer at P_{orb} = 6 hrs with a binary separation of about $a_{bin} \sim 2 R_{\odot}$
  - This is *much* smaller than the radius of the red giant progenitor of the WD ($R_{RG} \sim 100 R_{\odot}$)
  - At some point after the WD progenitor left the MS, both stars must have been inside the red giant envelope

    → Common Envelope Phase

- During interaction of binary with envelope, orbital energy is used to unbind the envelope

  → envelope ejection

  → spiral-in and close binary (pre-CV) formation

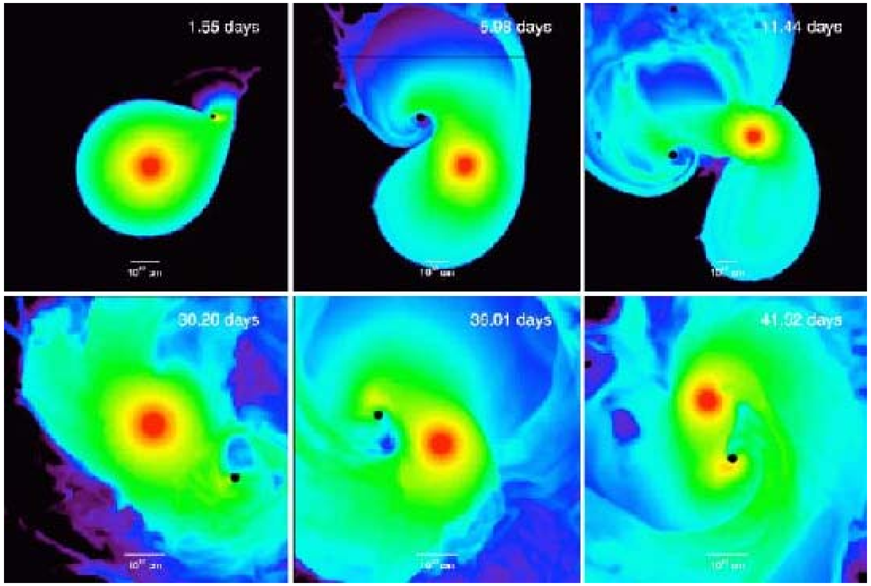
- CE evolution is rapid!

  → CE phase lasts less than a few thousand years!

The Common Envelope Phase: Physics

- The physics of the CE phase is extremely complex
  - CE phase encompasses huge range of size- and time-scales
  - CE ejection process is inherently 3-dimensional
  - Both hydrodynamic friction and gravitational torques matter
  - Envelope (and hence progenitor) structure matters
  - Additional energy sources? (Thermal / Recombination [Webbink 2008])

→ Proper treatment requires full 3-D high-resolution hydro simulations for each case
(see series of papers by Taam, Bodenheimer, Sandquist & collaborators)



The Common Envelope Phase: Recipes

- Calculating the properties of the zero-age CV population requires simulating the evolution of thousands of binary systems from birth to the onset of mass transfer
  - A full treatment of the CE phase for all these binaries is out of the question!

- Energy budget approach (Tutukov & Yungelson 1979; de Kool 1994; Politano 1996)
  - If the energy required to eject the envelope of the red giant comes exclusively from the orbital shrinkage of the WD + MS system, we must have

$$\Delta E_{env} = \alpha_{CE}\ \Delta E_{orb} \qquad \text{with } \alpha_{CE} \leq 1$$

- Angular momentum approach (Nelemans et al. 2000; Nelemans & Tout 2005)
  - Assume specific angular momentum carried away by the envelope is some fixed multiple of the initial specific angular momentum of the binary system

$$\frac{\Delta J_{orb}}{J_{orb}} = \gamma_{CE} \frac{\Delta M_{env}}{M_{1,i} + M_2}$$

Predictions vs Observations I

(based on α_{CE} approach)

	Prediction	Observation
Birthrate	$b \sim 10^{-3} - 10^{-2}\, yr^{-1}$ (de Kool 1992; Politano 1996)	$b \sim 10^{-4} - 10^{-3}\, yr^{-1}$ (Townsley & Bildsten 2004)
Space Density	$\rho \sim 10^{-5} - 10^{-4}\, pc^{-3}$ (de Kool 1992; Kolb 1993; Politano 1996)	$\rho \sim 10^{-5}\, pc^{-3}$ (Patterson 1998; Pretorius et al. 2007a)

Caveats:

- predicted numbers are a bit high
  - → selection effects? (see later)
- the rough agreement does not imply the adopted recipe must be correct
  - → Other recipes may predict similar *rates*, but different parameter *distributions*

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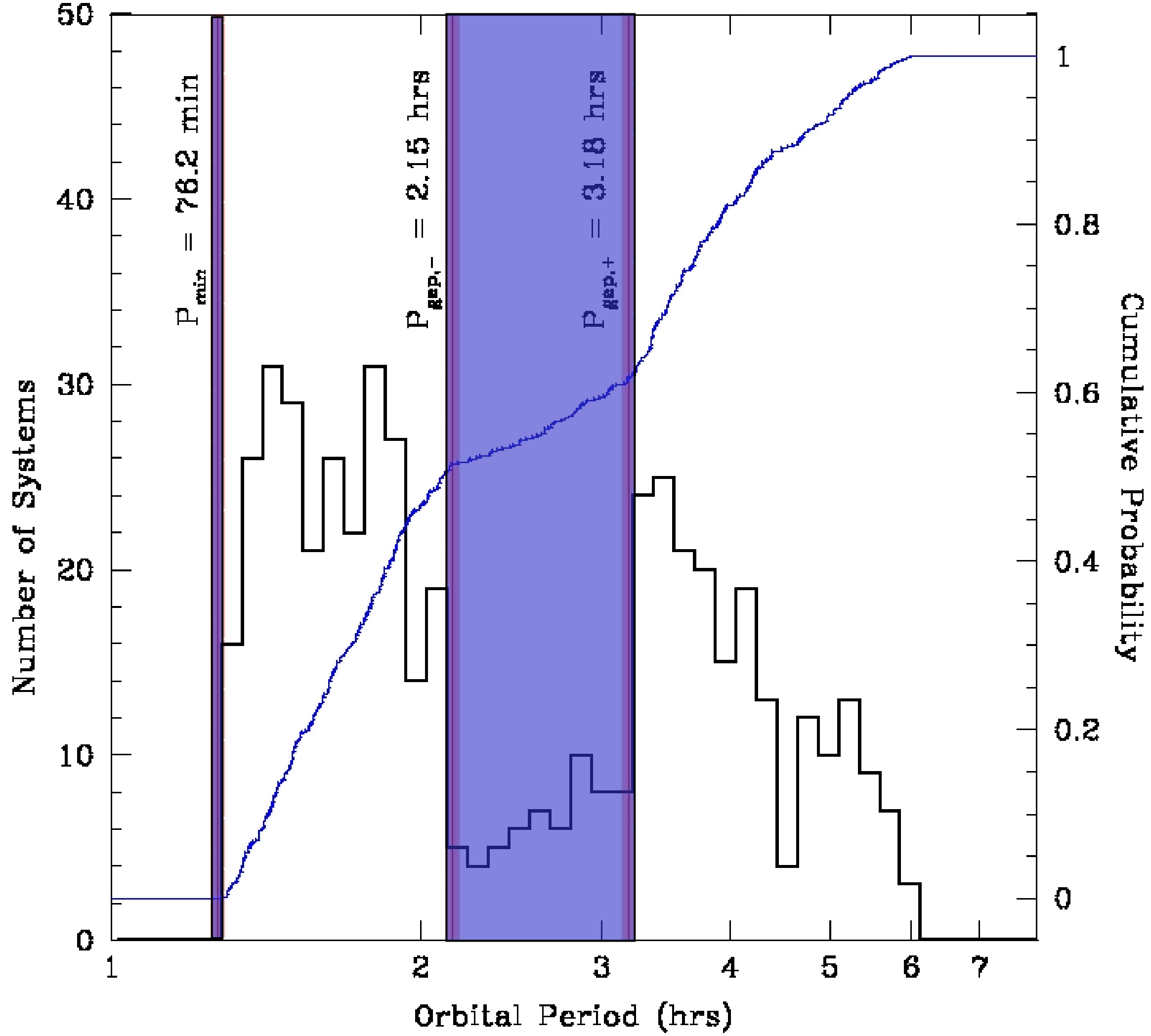
Part II: The Evolution of Cataclysmic Variables

The CV Period Distribution



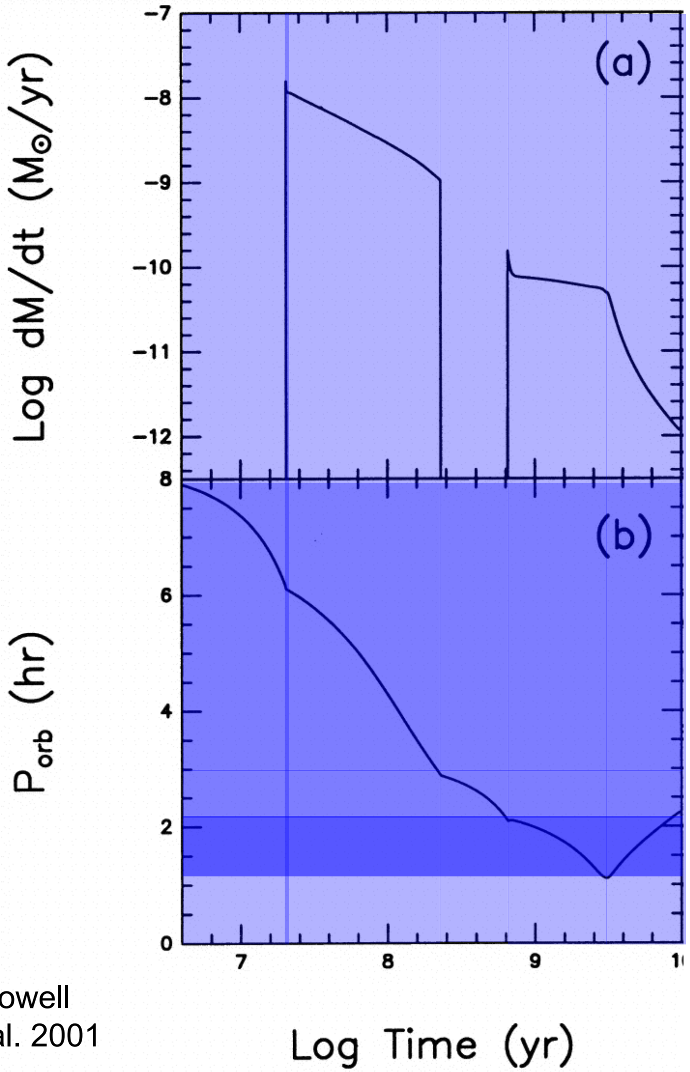
Knigge 2006

Two Key Features

- Clear "Period Gap" between 2-3 hrs
- Minimum period around 80 min

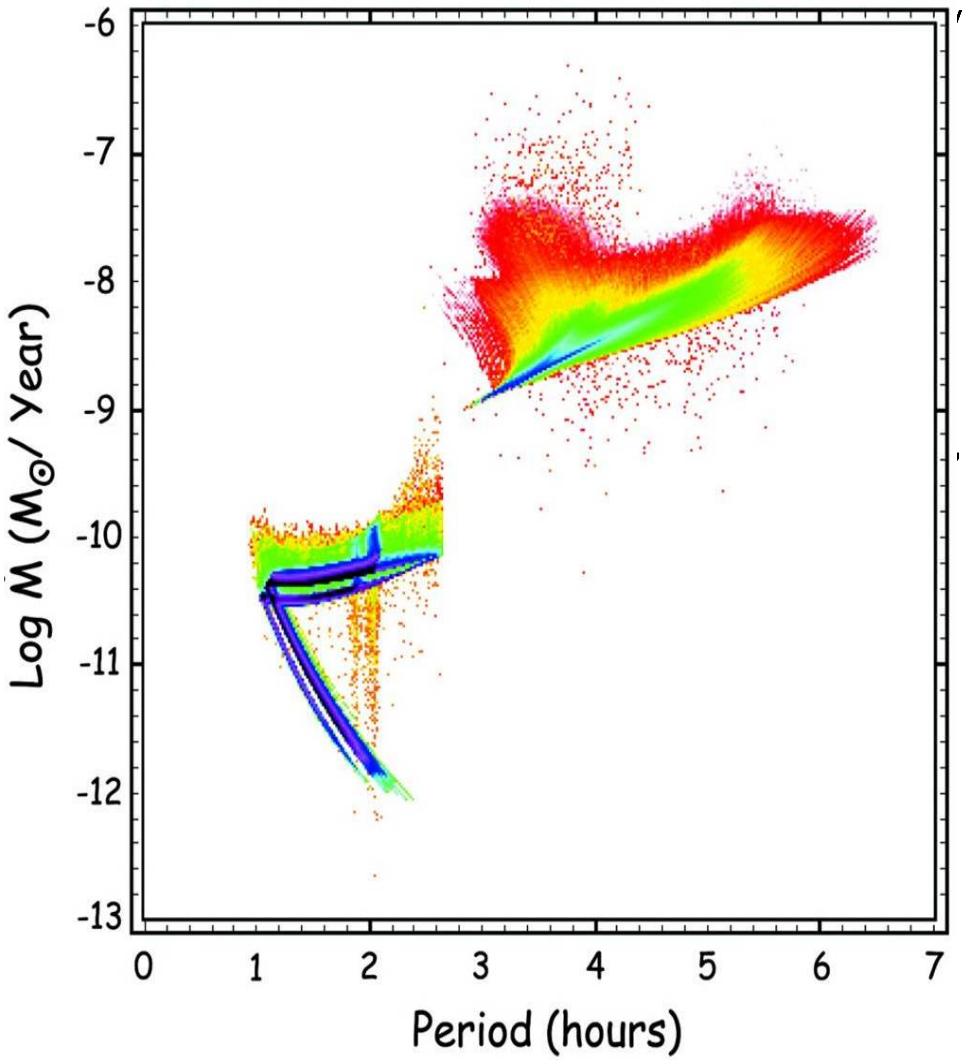
The Standard Model of CV Evolution:

Disrupted Magnetic Braking



Howell et al. 2001

Howell et al. 2001

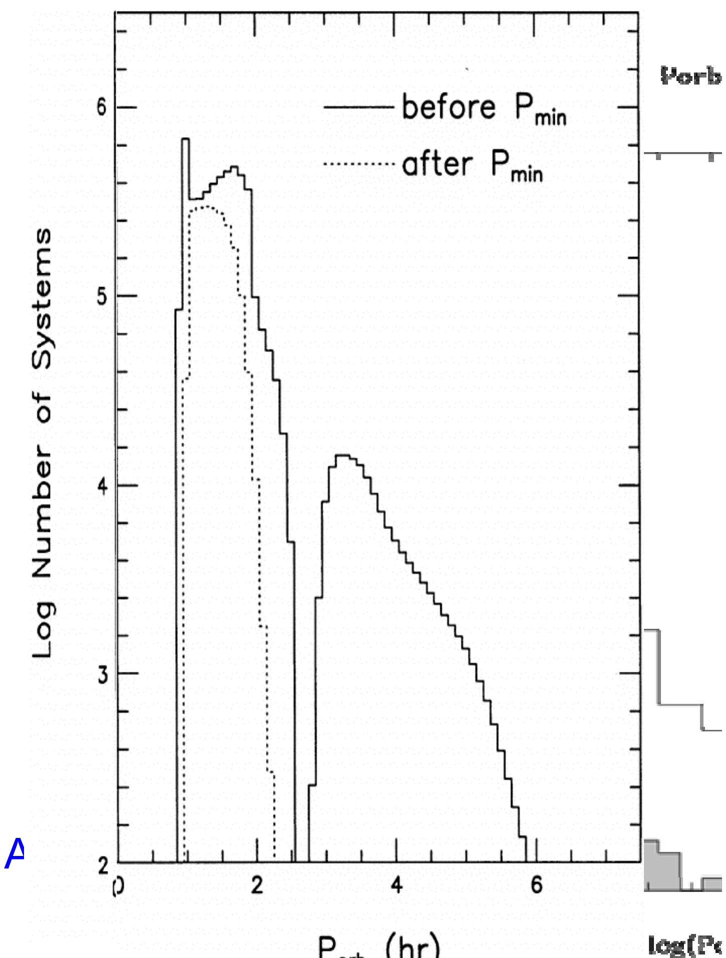


Predictions vs Observations II

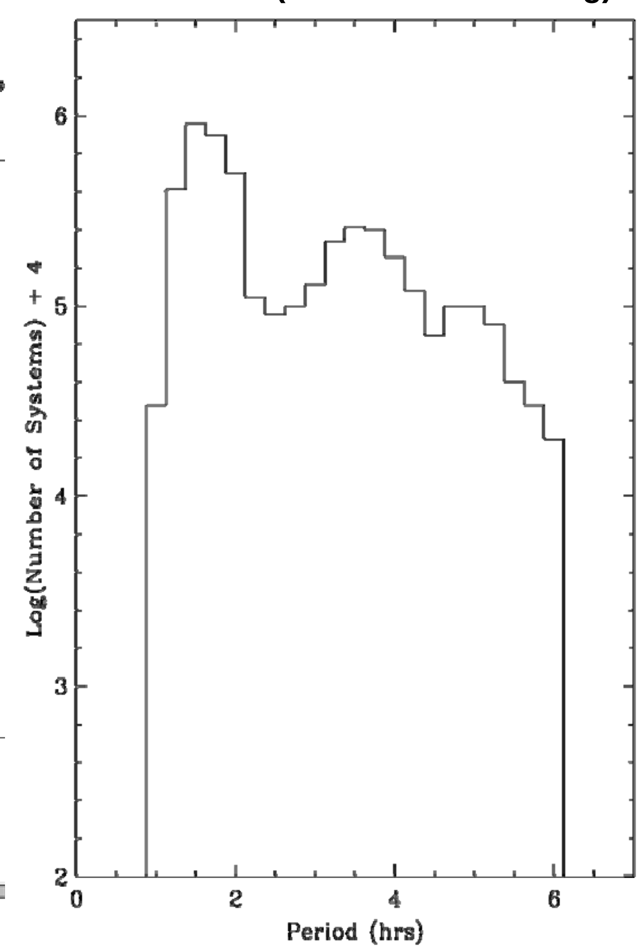
Gänsicke et al. (2009): The SDSS CV sample reveals the period sp

- Birthrate
- Space Density
- Period Gap
- N_{bounce}:N_{short}:N_{long}
- Minimum Period

Predicted (Howell et al 2001)

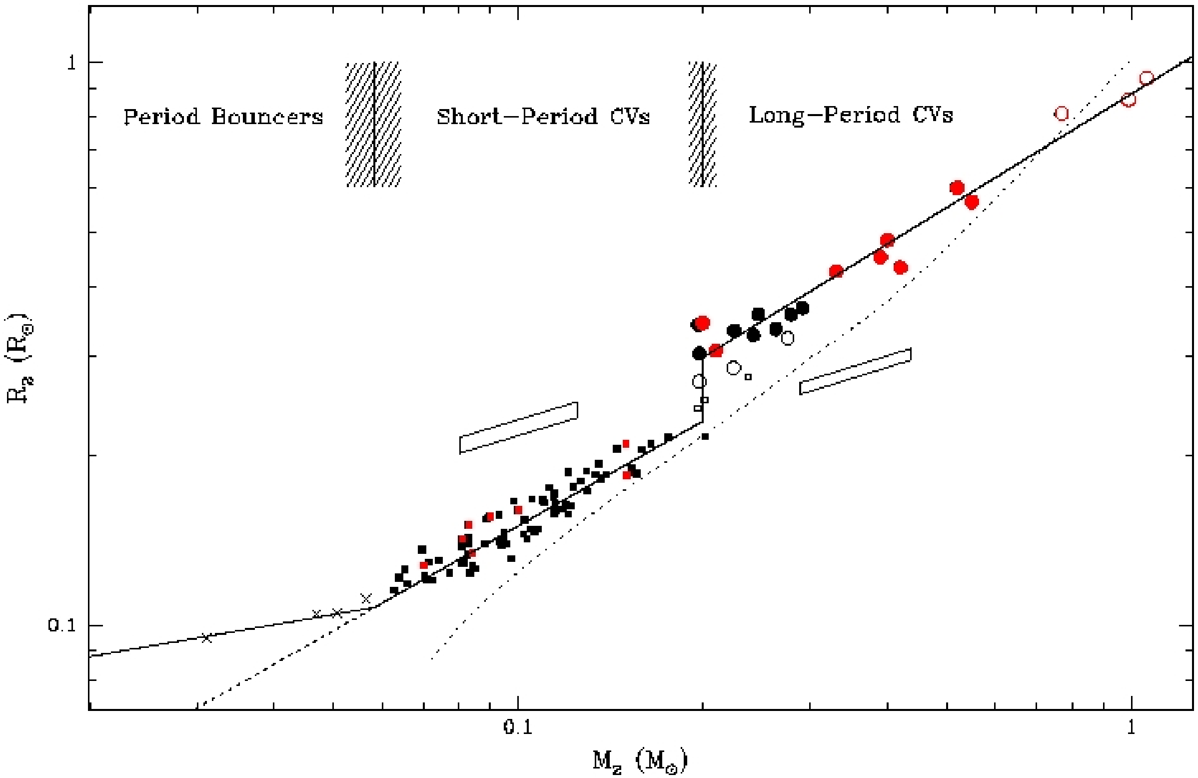


Observed (Ritter & Kolb catalog)



Is there actually any direct evidence for disrupted angular momentum loss?

(Patterson et al. 2005; Knigge 2006)



YES!

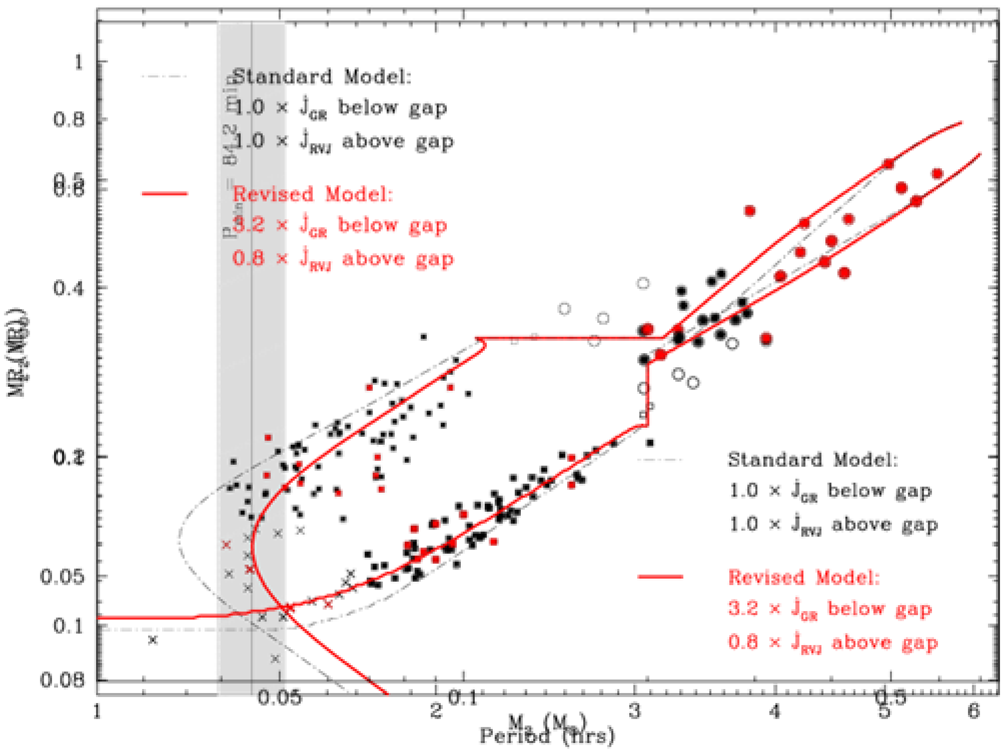
- Donors just above and below the gap have identical masses, but..
- …donors above the gap are ~30% larger

→ Exactly as predicted by disrupted AML scenario!

A Simple Revision:

Disruption yes, cessation no?

Knigge, Baraffe & Patterson 2009



- Could residual MB below the gap reconcile theory and observation (e.g. Patterson 1998)?
- Donor radii suggest that AML rate below the gap must be ~3 times larger than predicted by pure GR
- Similar to conclusions drawn from WD temperatures (Townsley & Gänsicke 2009)
- This revised model also naturally explains the observed location of the period minimum…
- …brings the predicted ratio of long-to-short period systems in line with observations…
- …and decreases the predicted space density for pre-bounce CVs

Problem solved?

Too early to say… (e.g. ask me about MB recipes and Littlefair et al 2008)

Part III: The Death of CVs

Are CVs Potential SN Ia Progenitors?

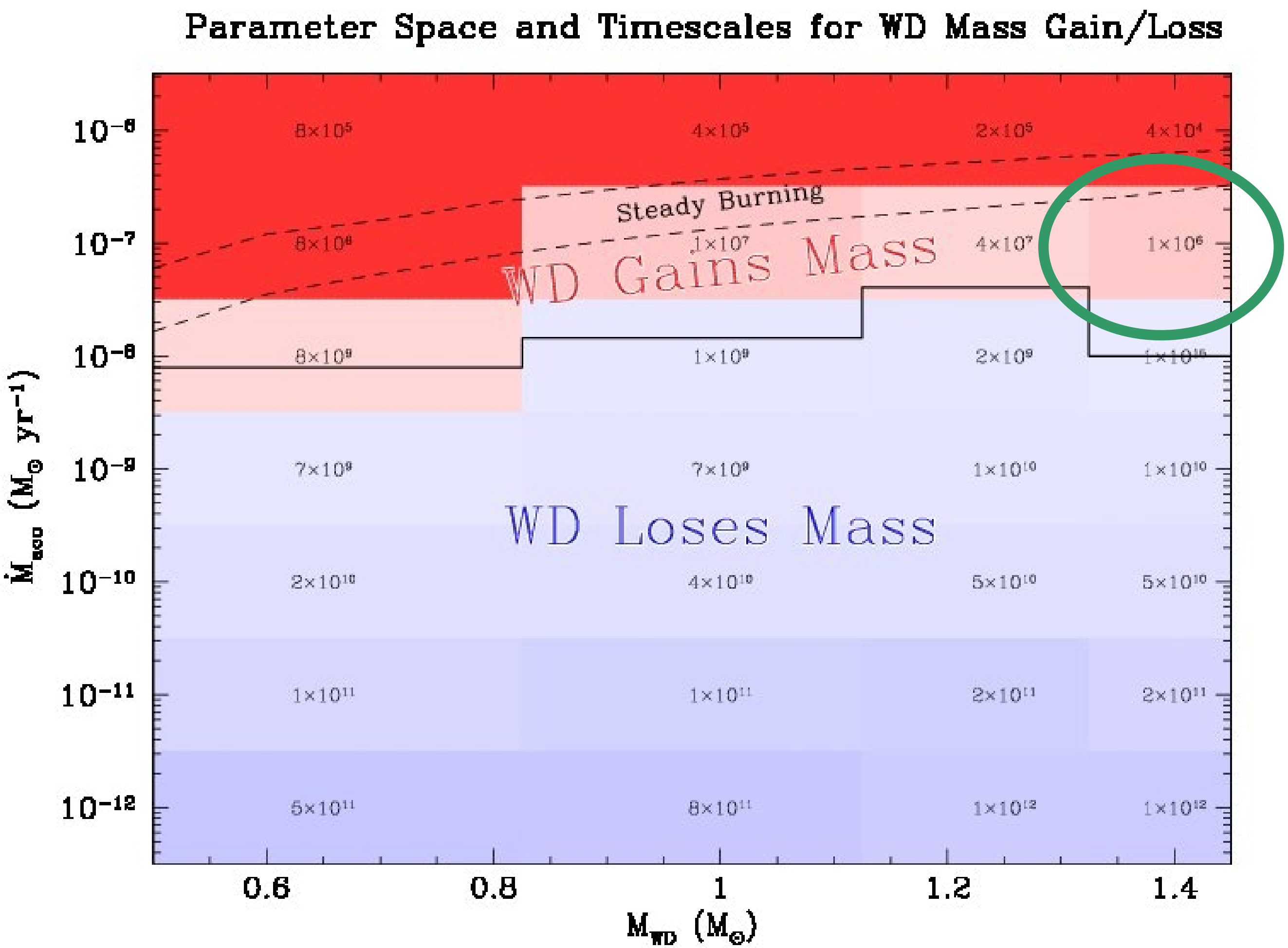
- Two key questions

(1) Do the WDs in CVs grow in mass?

- CVs undergo repeated nova eruptions
- Is M_{ej} lost during an outburst more or less than M_{acc} gained between eruptions?

(2) Are CV birth/death rates comparable to SN Ia rates?

Does the WD in a CV gain mass or loss mass?



- Nova models: mass gain is only possible for
  $\dot{M}_{acc} > 10^{-8}\ M_{\odot}\ yr^{-1}$
- CV evolution models do not achieve such high secular Mdot
- If possible at all, probably only for $M_{WD} > 1.2\ M_{\odot}$
- This regime probably leads to AIC, not SN Ia (e.g. Nomoto & Kondo 1990)

Data from Yaron et al. (2005)

Knigge, Baraffe & Patterson (2009)

CV Birth and Death Rates vs SN Ia Rates

- In a Milky-Way-like Galaxy, we have
  - SN Ia rate $\approx 3 \times 10^{-3}\ \mathrm{yr}^{-1}$ (e.g. Cappellaro et al. 1999; Manucci et al. 2005)
  - CV birth rate $\approx 10^{-4} - 10^{-2}\ \mathrm{yr}^{-1}$ (e.g. de Kool 1992; Politano 1996; Townsley & Bildsten 2004)

- A large fraction of CVs would have to end up as SN Ia in order to contribute significantly to overall SN Ia population

- Seems impossible to reconcile with tight constraints on M_{WD} and Mdot implied by nova models

  → **Ordinary CVs probably do not produce significant numbers of SN Ia**

- Better bets (within the single-degenerate scenario):
  - Supersoft sources
  - Symbiotic stars
  - V458 Vul-like weirdos? (ask me!)

Summary

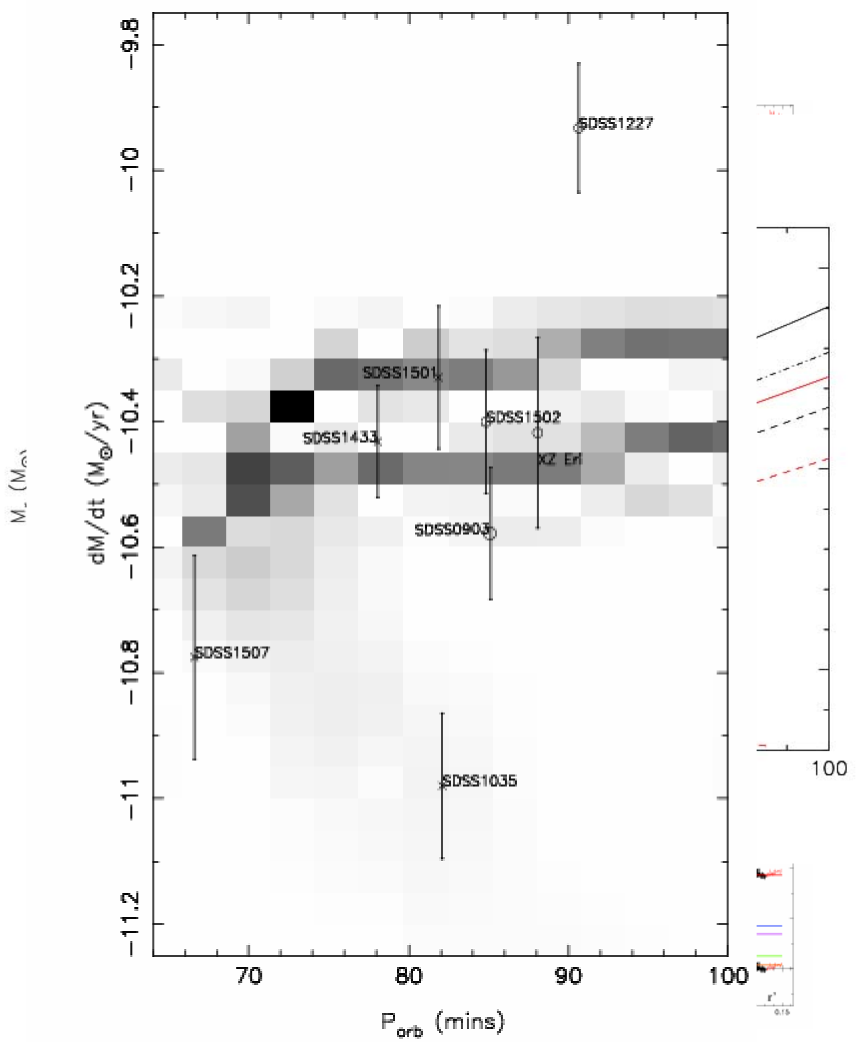
- Our fundamental framework for the formation and evolution of CVs is built on two key physical processes
  - Common envelope evolution
  - Disrupted magnetic braking
- This basic framework is probably correct
  - Birth rate and space density predictions are in the right ballpark
  - We have direct evidence that disrupted AML is responsible for the period gap
- However, neither of these two processes is well understood theoretically

  → ***Improved models and tests of CE evolution and MB are vital!***

- The standard disrupted MB model is also in conflict with several observational constraints
  - Residual MB below the gap is a promising way to overcome these
- Ordinary CVs are unlikely to contribute substantially to the SN Ia rate

Bonus Slides…

Problems with the Revised Model?



- Littlefair et al. (2008) have carried out comprehensive eclipse modelling for a sample of short-period CVs

  Good news: Donors are confirmed to be larger than predicted by standard model, in line with revised model

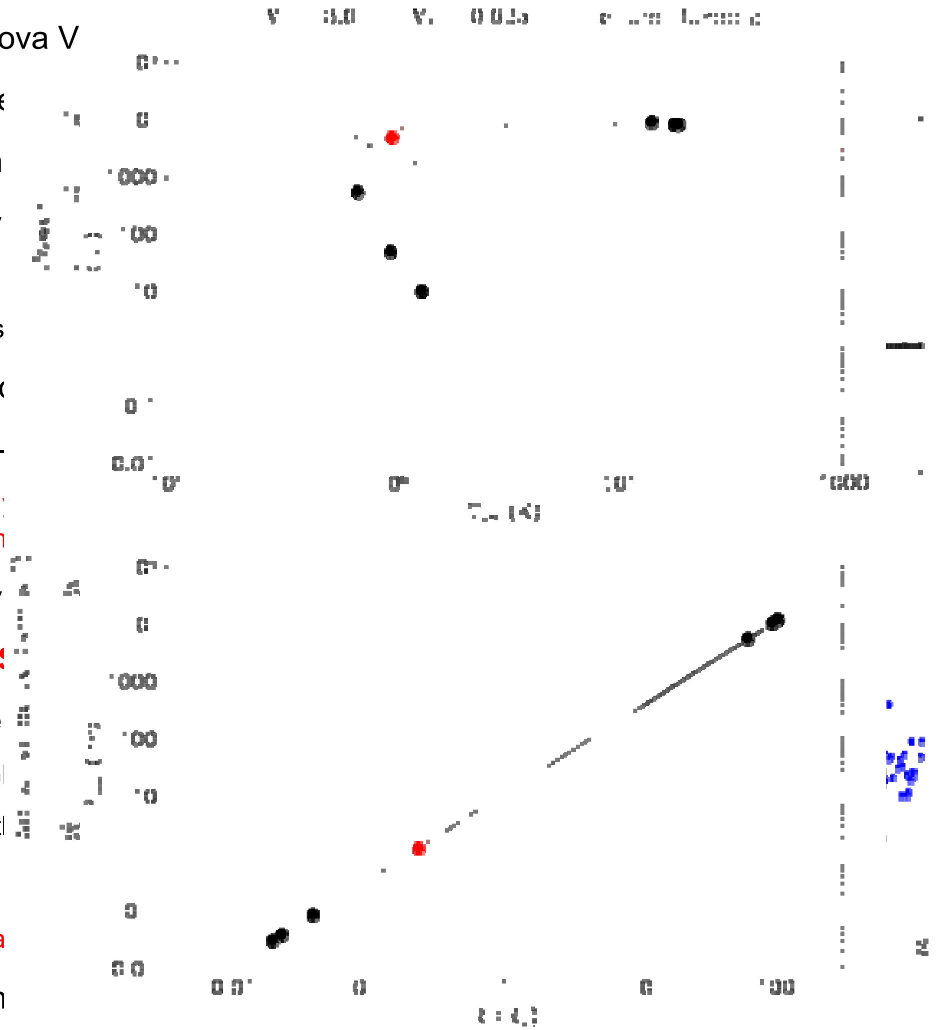
  Bad news: Combination of WD masses and temperatures imply accretion rates in line with standard (pure GR) model

  Which binary component is lying?

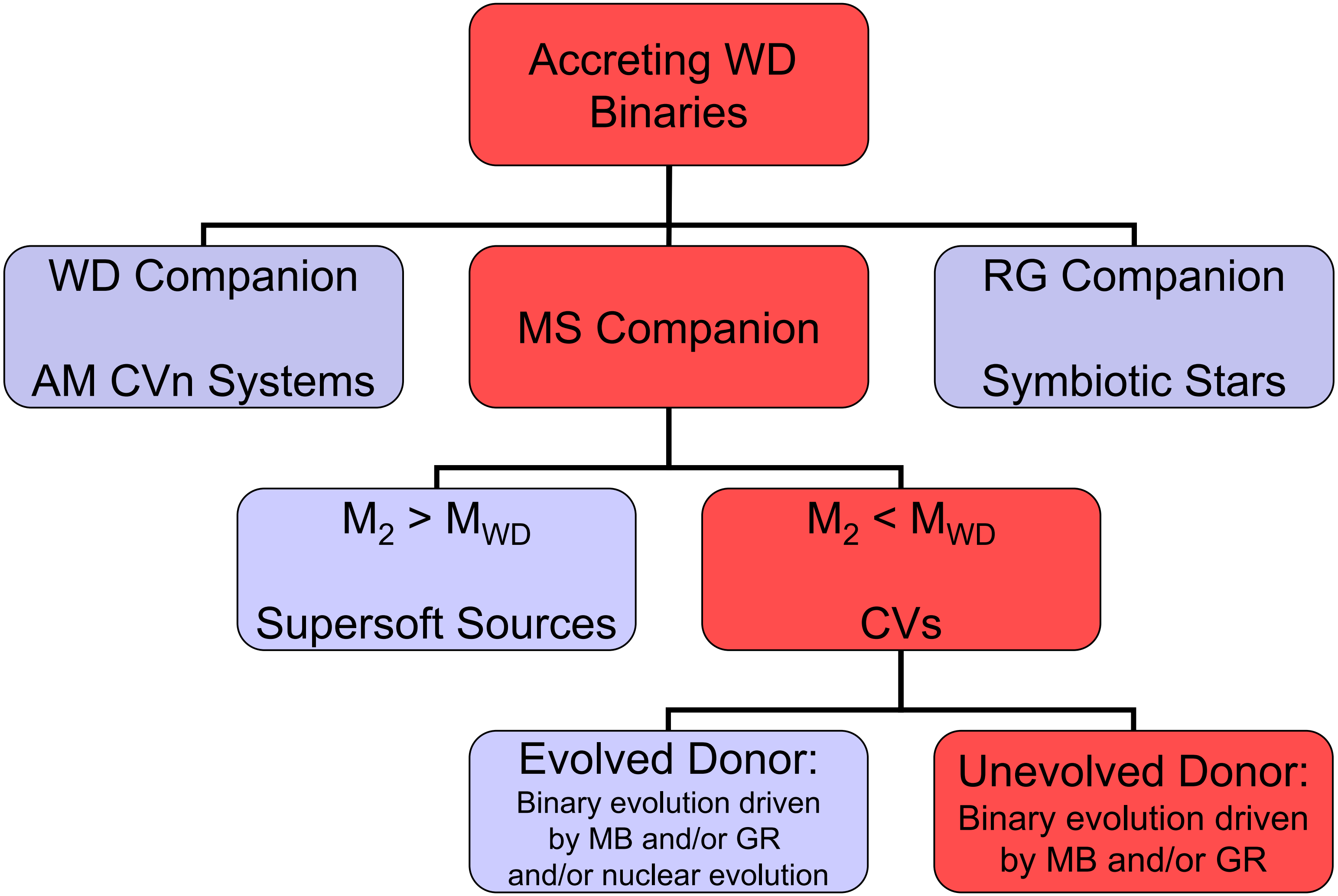
  – Donors: is the extra bloating due to magnetic activity, not mass loss?

  – WDs: are we not measuring the secular average mass transfer rate?

V458 Vul: A Bizarre SN Ia Progenitor?

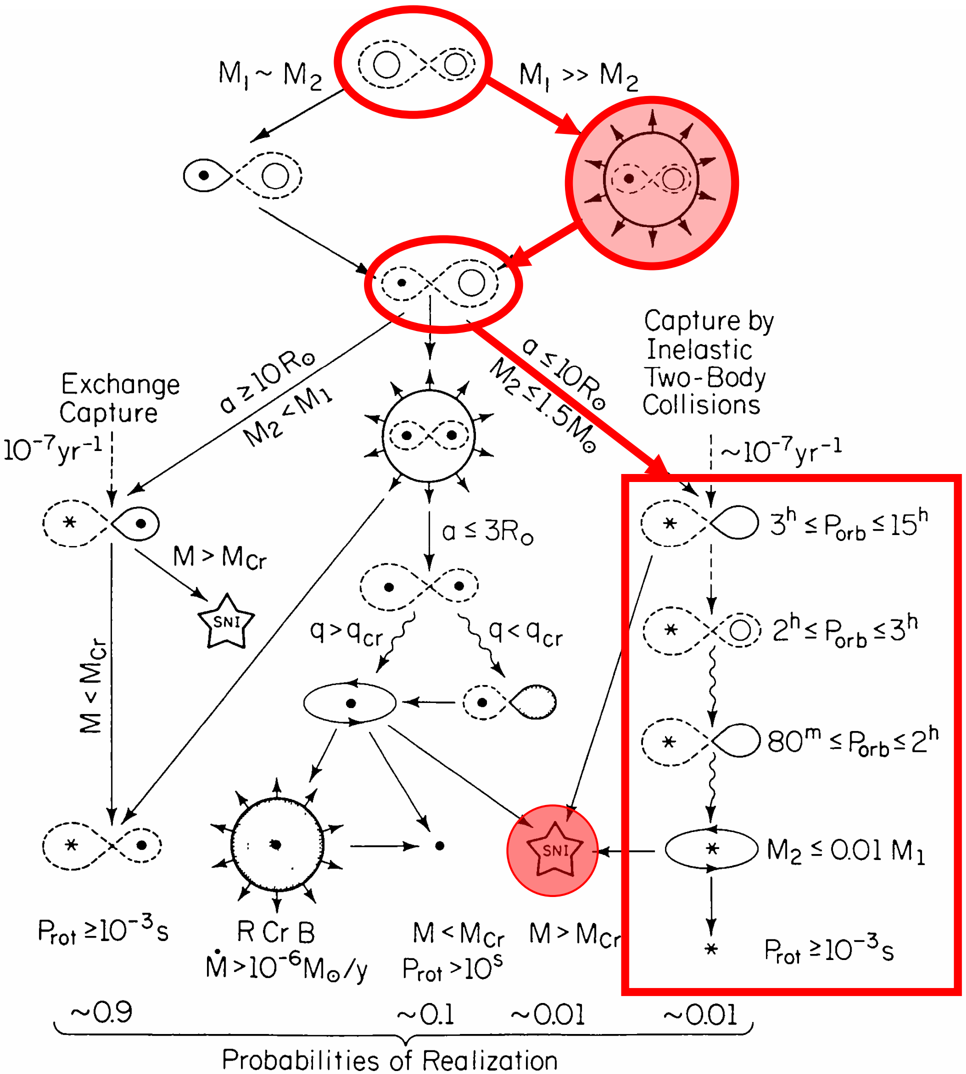
- V458 Vul = Nova V
- Nova characte
- Pre-explosion  ound the progenitor
- Spectroscopy ula (Wesson et al. 2008)
  - Is the PN
  - Or is it as
- Ionization mo eting WD is not ruled out
- IPHAS follow- (Rodriguez-Gil et al. 2009)
  - Amazingl erred from ionization and spectral n
- If this is really
  - **AIC or S**
- But the whole
  - The PAG ontact with the Roche lobe???
  - On the ot ale for orbital shrinkage
- Amazing and
  - If this cha entury in the Milky Way!
- Follow-up con aints on binary parameter and confirm or refu

CVs in the Zoo of Accreting White Dwarfs



CVs as Close Binaries:

Formation, Evolution, Relevance



Iben 1991

- Most binaries interact at some stage of their evolution…
- …but long-lived, *stable* interaction is relatively rare
- CVs represent one of the most important stable interaction channels
- pre-CV evolution involves common envelope (CE) phase
- CV evolution is driven entirely by angular momentum losses
- CE phase and AML are also key to other close binaries
- some CVs may become SN Ia

How well do we understand magnetic braking?

A compendium of widely used recipes

- Verbunt & Zwaan (1981)
  - Skumanich (1972): $v_{eq} \sim 10^{14} t_{yr}^{-1/2}\ cm\ s^{-1}$ + solid body rotation: $J_2 = k^2 M_2 R_2^2 \Omega$

$$\boxed{\dot{J}_{VZ} = -5\times10^{-27} k^2 M_2 R_2^4 \Omega^3}$$

- Rappaport, Verbunt & Joss (1983)
  - VZ plus ad-hoc power-law in R_2

$$\boxed{\dot{J}_{RVJ} = \dot{J}_{VZ}\left(R_\odot / R_2\right)^{\gamma-4}}$$

- Kawaler (1988)
  - Theoretically motivated; (a=1, n=3/2 ➔ Skumanich)

$$\boxed{\dot{J}_{Kaw} = -K_W \dot{M}_{w,14}^{1-(2n/3)} \left(M_2/M_\odot\right)^{-n/3} \left(R_2/R_\odot\right)^{2-n} \Omega^{1+(4an/3)}}$$

- Andronov, Pinsonneault & Sills (2003)
  - Saturated AML prescription based on open cluster data; for CVs $\Omega > \Omega_{crit}(M_2)$

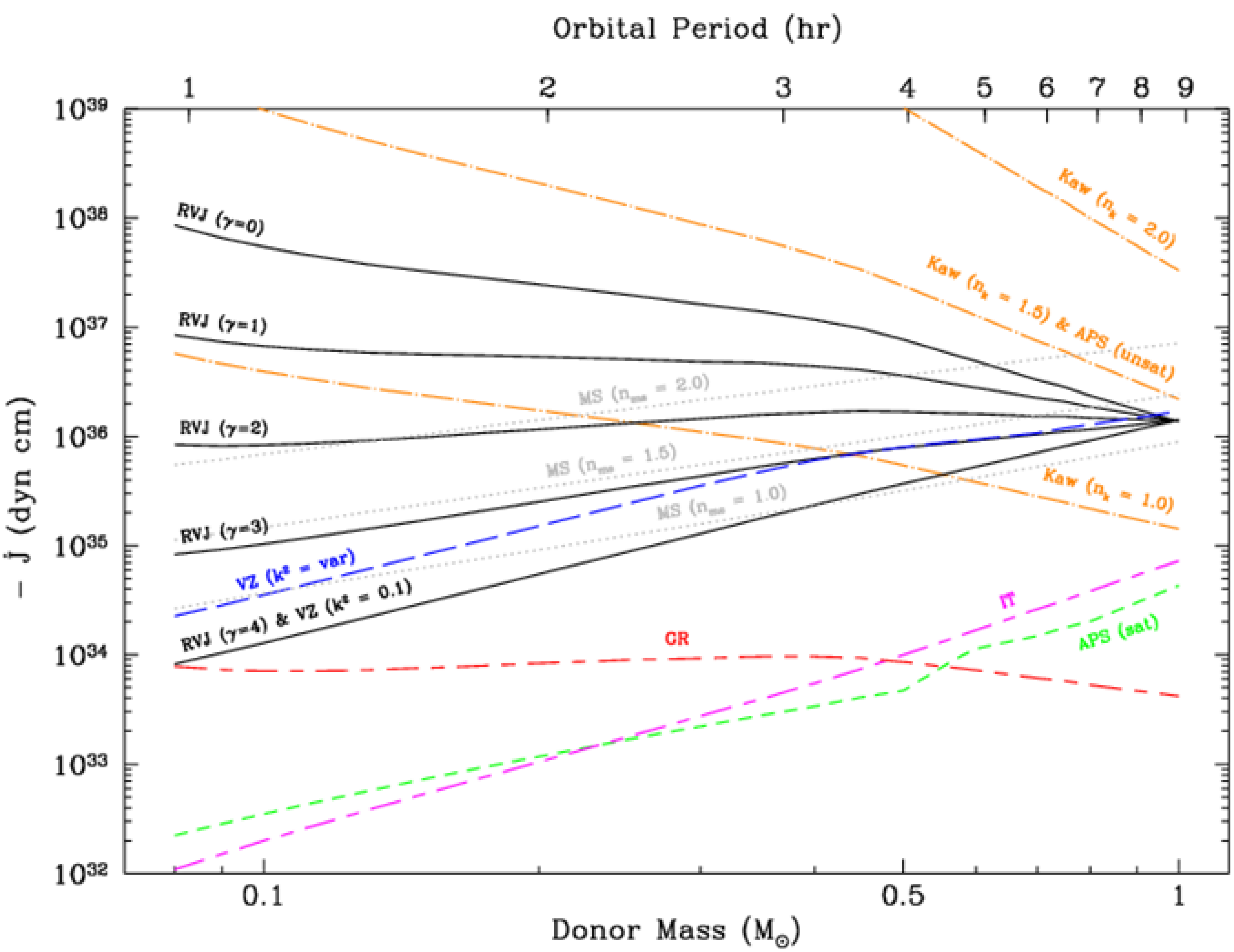
$$\dot{J}_{APS} = \begin{cases} \dot{J}_{Kaw;(n=3/2)} & \propto \Omega^3 \quad \ldots \quad \Omega < \Omega_{crit} \\ \dot{J}_{Kaw;(n=3/2)} \left(\Omega_{crit}/\Omega\right)^2 & \propto \Omega \quad \ldots \quad \Omega > \Omega_{crit} \end{cases}$$

- Ivanova & Taam (2003)
  - Another saturated recipe; for CVs $\Omega > \Omega_X$

$$\dot{J}_{IT} = \begin{cases} K_j \left(R_2/R_\odot\right)^4 \left(\Omega/\Omega_\odot\right)^3 & \ldots \quad \Omega < \Omega_X \\ K_j \left(R_2/R_\odot\right)^4 \left(\Omega^{1.3}\Omega_X^{1.7}/\Omega_\odot^3\right) & \ldots \quad \Omega > \Omega_X \end{cases}$$

How well do we understand magnetic braking?

We don't!



- Orders of magnitude differences between recipes at fixed P
- Different recipes do not even agree in basic form!
- The saturated ones don't even beat GR below ~0.5$M_\odot$

Knigge, Baraffe & Patterson 2009