The formation of (double-lined) double white dwarfs

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Outline

Observed double white dwarfs

System	P_{orb} (d)	a_{orb} ($R_\odot$)	M_1 ($M_\odot$)	M_2 ($M_\odot$)	q_2 (M_2/M_1)	$\Delta\tau$ (Myr)
WD 0135–052	1.556	5.63	0.52 ± 0.05	0.47 ± 0.05	0.90 ± 0.04	350
WD 0136+768	1.407	4.99	0.37	0.47	1.26 ± 0.03	450
WD 0957–666	0.061	0.58	0.32	0.37	1.13 ± 0.02	325
WD 1101+364	0.145	0.99	0.33	0.29	0.87 ± 0.03	215
PG 1115+116	30.09	46.9	0.7	0.7	0.84 ± 0.21	160
WD 1204+450	1.603	5.74	0.52	0.46	0.87 ± 0.03	80
WD 1349+144	2.209	6.59	0.44	0.44	1.26 ± 0.05	—
HE 1414–0848	0.518	2.93	0.55 ± 0.03	0.71 ± 0.03	1.28 ± 0.03	200
WD 1704+481a	0.145	1.14	0.56 ± 0.07	0.39 ± 0.05	0.70 ± 0.03	-20[a]
HE 2209–1444	0.277	1.88	0.58 ± 0.08	0.58 ± 0.03	1.00 ± 0.12	500

[a] Unclear which white dwarf is older

$*2$ is supposedly the latest-formed WD

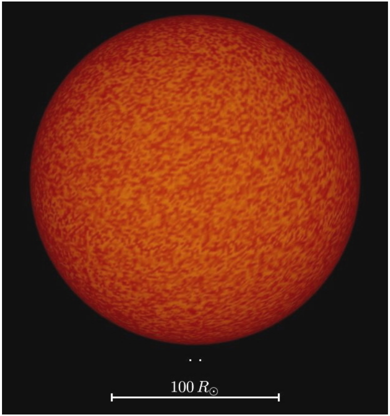
See references in Maxted et al. (2002), Nelemans & Tout (2005) and MvdS et al. (2006)

- WD masses $\sim 0.3 - 0.7\ M_\odot$
- Orbital separations $\sim 0.5 - 6\ R_\odot$ ($+47\ R_\odot$)

Common Envelope

Properties of observed white dwarfs:

- Average orbital separation:
  - $7\,R_\odot$
- Typical progenitor system:
  - $M_c \gtrsim 0.3\,M_\odot$
  - $R_* \sim 100\,R_\odot$



Classical α-common envelope (CE; spiral-in):

- orbital energy is used to expel envelope (Webbink, 1984):

$$E_{\rm bind} = \alpha_{\rm CE}\left[\frac{G\,M_{1\rm f}\,M_2}{2\,a_{\rm f}} - \frac{G\,M_{1\rm i}\,M_2}{2\,a_{\rm i}}\right]$$

- $\alpha_{\rm CE}$ is the common-envelope efficiency parameter

Assumptions:

- Envelope ejection occurs much faster than nuclear evolution, hence:
  - core mass does not grow during envelope ejection
  - no accretion by companion during envelope ejection
- The timescale does not have to be the dynamical timescale(!)

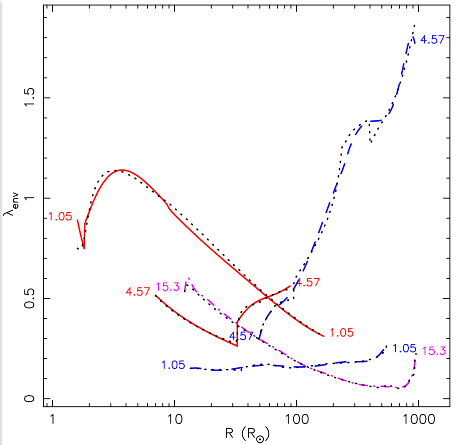
Envelope structure parameter

- Detailed stellar model is needed to compute $E_{\rm bind}$
- Use $\lambda_{\rm env}$ to approximate $E_{\rm bind}$ from basic parameters (Webbink, 1984; De Kool et al., 1987)

$$\lambda_{\rm env} \equiv \frac{G\,M\,M_{\rm env}}{R\,E_{\rm bind,env}}$$

$$-\frac{G\,M\,M_{\rm env}}{R} = \alpha_{\rm CE}\,\lambda_{\rm env}\,\Delta E_{\rm orb}$$

- Smaller $\lambda_{\rm env}$ indicates more centrally concentrated envelope
- Often, a constant value for $\lambda_{\rm env}$ is assumed in population-synthesis codes:
  - $\lambda_{\rm env} = 0.5$ (*e.g.* De Kool 1987; Nelemans et al., 2000; Hurley et al., 2002)
  - $\alpha_{\rm CE}\lambda_{\rm env} = 0.5, 1.0$ (*e.g.* Belczynski et al., 2008)
- Value of $\lambda_{\rm env}$ is far from constant (*e.g.* Dewi & Tauris, 2000; MvdS et al., 2006)

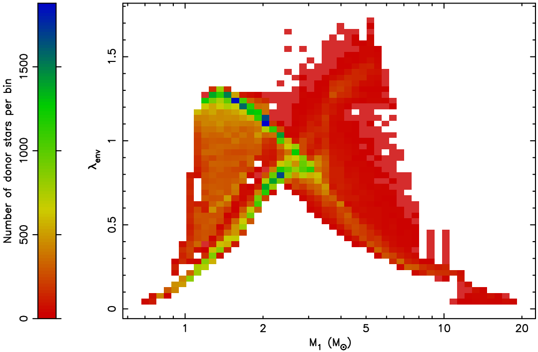


(Loveridge et al., 2011)

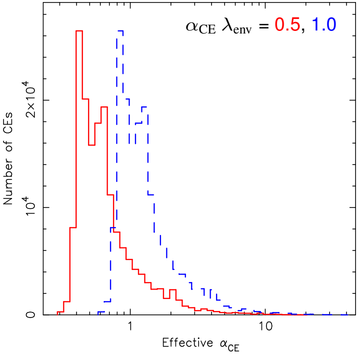
Envelope structure parameter

Properties of 165,007 CEs

	RGB	AGB	Total
Survivors	16.1%	31.8%	48.0%
Mergers	45.4%	6.6%	52.0%
Total	61.5%	38.5%	100.0%

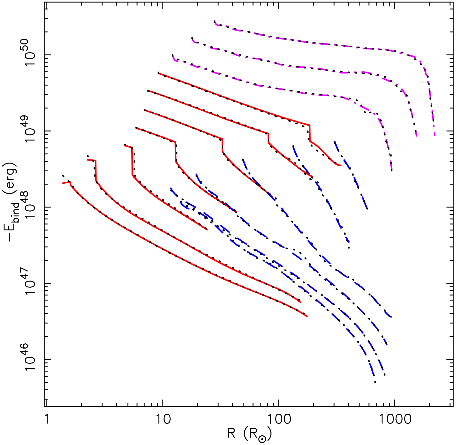


MvdS et al. (2010)



- Implicit $\alpha_{CE} > 1$ for 16% and 64% of CEs

Fits for the binding energy



low-mass RGB low-mass AGB high-mass GB
dots: models, coloured lines: fits

$$E_{\rm bind} = \int_{M_{\rm c}}^{M_{\rm s}} \left(E_{\rm int}(m) - \frac{Gm}{r(m)} \right) {\rm d}m$$

$$\log\left(\frac{-E_{\rm bind}}{\rm erg}\right) \approx E_0 + \Lambda(M_0, M) \times \sum_{m,r} \alpha_{m,r} \left[\log\left(\frac{M}{M_\odot}\right)\right]^m \left[\log\left(\frac{R}{R_\odot}\right)\right]^r$$

- ev / STARS / TWIN (Eggleton 1971, 1972, ...)
- 73 models, $0.8\,M_\odot \leq M \leq 100\,M_\odot$
- fit as a function of ZAMS mass, current mass and current radius
- 6 different metallicities ($Z = 10^{-4} - 0.03$)
- Λ correction factor for wind mass loss
- separate fits for recombination energy

Andrew Loveridge et al. (2011)

Observed double white dwarfs

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Formation scenarios

Stable + unstable MT

MS + MS

↓ Stable M.T. (cons./part.cons.) ↓

WD + MS

↓ Unstable M.T. (α-CE) ↓

WD + WD

Unstable + unstable MT

MS + MS

↓ Unstable M.T. (γ-EE) ↓

WD + MS

↓ Unstable M.T. (α-CE, γ-EE) ↓

WD + WD

Envelope ejection with angular-momentum conservation

- Average specific angular momentum of the system (Nelemans et al., 2000):

$$\frac{J_\mathrm{i} - J_\mathrm{f}}{J_\mathrm{i}} = \gamma_\mathrm{s} \frac{M_\mathrm{1i} - M_\mathrm{1f}}{M_\mathrm{tot,i}} \quad (\gamma_\mathrm{s} \sim 1.5)$$

- Specific angular momentum of the donor (MvdS et al., 2006):

$$\frac{J_\mathrm{i} - J_\mathrm{f}}{J_\mathrm{i}} = \gamma_\mathrm{d} \frac{M_\mathrm{1i} - M_\mathrm{1f}}{M_\mathrm{tot,f}} \frac{M_\mathrm{2i}}{M_\mathrm{1i}} \quad (\gamma_\mathrm{d} \sim 1.0)$$

- Specific angular momentum of the accretor (MvdS et al., 2006):

$$\frac{J_\mathrm{i} - J_\mathrm{f}}{J_\mathrm{i}} = \gamma_\mathrm{a} \left[1 - \frac{M_\mathrm{tot,i}}{M_\mathrm{tot,f}} \exp\left(\frac{M_\mathrm{1f} - M_\mathrm{1i}}{M_2}\right)\right] \quad (\gamma_\mathrm{a} \sim 1.0)$$

Unstable MT results: overview

Select systems with:

- $0.8 < \alpha_{\rm CE} < 1.2$
- $1.46 < \gamma_{\rm s} < 1.79$
- $0.9 < \gamma_{\rm a,d} < 1.1$

System	1: $\gamma_{\rm s}\alpha_{\rm CE}$	2: $\gamma_{\rm s}\gamma_{\rm s}$	3: $\gamma_{\rm a}\alpha_{\rm CE}$	4: $\gamma_{\rm a}\gamma_{\rm a}$	5: $\gamma_{\rm d}\alpha_{\rm CE}$	6: $\gamma_{\rm d}\gamma_{\rm a}$	Best:
0135	$-/-$	$+/\sim$	$+/\sim$	$-/-$	$+/\sim$	$+/\sim$	2,3,5,6
0136	$+/+$	$+/+$	$+/\sim$	$+/\sim$	$+/+$	$+/+$	1,2,5,6
0957	$+/+$	$+/+$	$-/-$	$+/-$	$+/+$	$+/+$	1,2,5,6
1101	$+/\sim$	$+/-$	$+/-$	$-/-$	$+/\sim$	$+/\sim$	1,5,6
1115	$+/\sim$	$+/+$	$+/\sim$	$+/\sim$	$+/+$	$+/+$	2,5,6
1204	$-/-$	$+/-$	$+/-$	$+/-$	$+/-$	$+/+$	6
1349	$+/+$	$+/+$	$+/+$	$+/+$	$+/+$	$+/+$	1–6
1414	$-/-$	$+/+$	$-/-$	$+/+$	$-/-$	$+/+$	2,4,6
1704a	$+/-$	$+/-$	$-/-$	$-/-$	$-/-$	$-/-$	1,2
1704b	$+/-$	$+/-$	$-/-$	$+/-$	$+/-$	$+/-$	1,2,4,5,6
2209	$+/+$	$+/+$	$-/-$	$-/-$	$+/\sim$	$+/+$	1,2,6
Best	$7\times$	$9\times$	$2\times$	$3\times$	$7\times$	$10\times$	

Column 1: $+$: α, γ within range, $-$: α, γ outside range

Column 2: $+$: $\Delta(\Delta t) < 50\%$, $\sim$: $50\% < \Delta(\Delta t) < 500\%$, $-$: $\Delta(\Delta t) > 500\%$

DWD summary/conclusions so far

Stable, conservative mass transfer:

- Nelemans et al. (2000); MvdS et al. (2006)
- Analytic models and detailed binary-evolution models give qualitatively same results
- We can reproduce perhaps 1–4 out of 10 systems, all with $\alpha_{\rm CE} > 1.6$
- **Conservative MT + CE cannot explain the observed double white dwarfs**

Unstable mass transfer:

- Unstable envelope ejection can explain the observed double white dwarfs
- Several EE descriptions can reconstruct observed masses and periods
- In addition, $\gamma_{\rm s}\gamma_{\rm s}$ and $\gamma_{\rm d}\gamma_{\rm a}$ can explain most observed cooling-age differences

But:

- What do $\gamma_{\rm s,d,a}$ mean?
- Is $q_{\rm crit}$ a good condition for stabilty of MT?
- What about stable, *non-conservative* MT?
- Do stellar winds have any influence?

System mass loss during stable mass transfer

Mass loss during mass transfer:

- “stable, non-conservative mass transfer [. . .] would stabilise the mass transfer.” (MvdS et al., 2006)
- “[the DWDs] evidently evolved through quasi-conservative mass transfer.” (Webbink, 2008)

This leads to:

- stable MT initiated at longer orbital periods ($q_{\rm crit}$ changes)
- stable MT initiated for almost equal-mass binaries
- stable MT from more-massive donor stars
- shorter post-MT orbits due to AM loss

Hence:

- more massive primaries
- less massive secondaries
- more (low-mass) DWDs with $q \sim 1$

Stability of and conservation factor during mass transfer

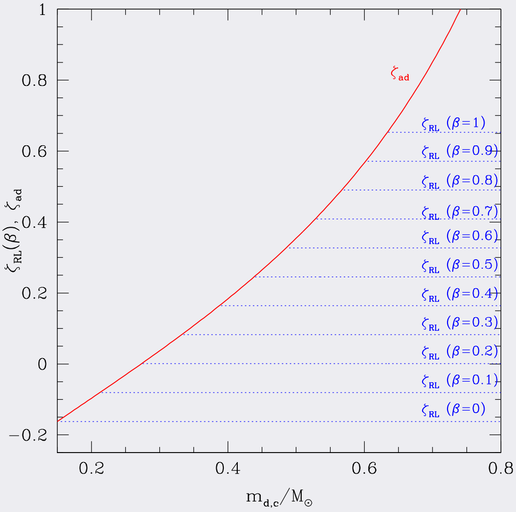
Response of donor star and Roche lobe to mass loss:

$$\zeta_{\rm ad} \equiv \left(\frac{d\log R_*}{d\log M_*}\right)_{\rm ad} = f\left(\frac{M_c}{M_*}\right)$$

$$\zeta_{\rm Rl} \equiv \frac{d\log R_{\rm Rl}}{d\log M_*} = f(q,\beta)$$

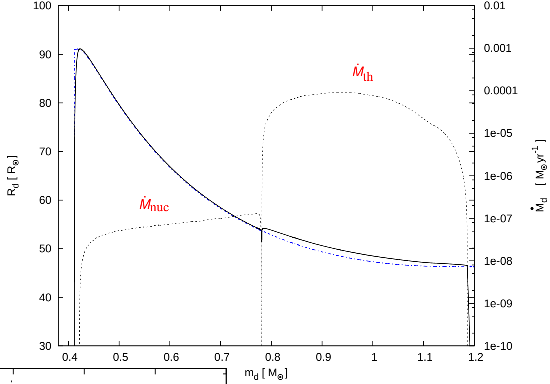
- If $\zeta_{\rm ad} \gtrsim \zeta_{\rm Rl}$ (*i.e.*, $\dot{R}_* \lesssim \dot{R}_{\rm Rl}$), mass transfer is dynamically stable (Hjellming & Webbink, 1987)
- β: mass-conservation factor; $\dot{M}_2 = -\beta\dot{M}_1$

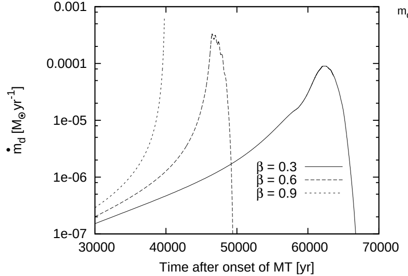
$M_1 = 1.2\,M_\odot$, $M_2 = 1.1\,M_\odot$



Tyrone Woods et al., 2012

Thermal and nuclear mass transfer



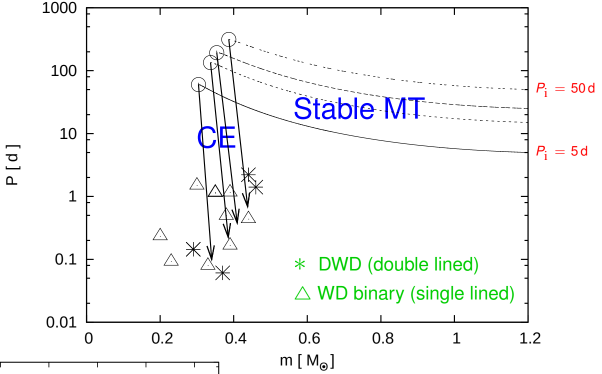


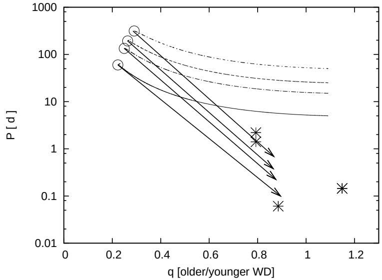
Default system:

- $M_i = 1.2 + 1.1\,M_\odot$ $\quad (q_i \approx 1.09)$
- $P_i = 100\,\mathrm{d}$ $\quad (M_{c,1} \approx 0.35\,M_\odot)$
- $\beta = 0.3$

Woods et al., 2012

Formation of low-mass DWDs through stable mass transfer





Initial systems:

- $M_\mathrm{i} = 1.2 + 1.1\,M_\odot$ $\quad (q_\mathrm{i} \approx 1.09)$
- $P_\mathrm{i} = 5, 15, 25, 50\,\mathrm{d}$
- $\beta = 0.3$

Woods et al., 2012

Population synthesis

BSE

- BSE/popbin (Hurley et al., 2000, 2002)
- Updated stability criterion (ζ instead of $q_{\rm crit}$) for giants

Initial population

- 200 million ZAMS binaries; constant star-formation rate
- Kroupa IMF, $0.8\,M_\odot \leq M_1 \leq 10\,M_\odot$
- Uniform q_i distribution; $0.1\,M_\odot \leq M_2 \leq M_1$
- Uniform distribution in $\log(a_i)$, $5\,R_\odot \leq a \leq 10^4\,R_\odot$; $e = 0$

Assumptions

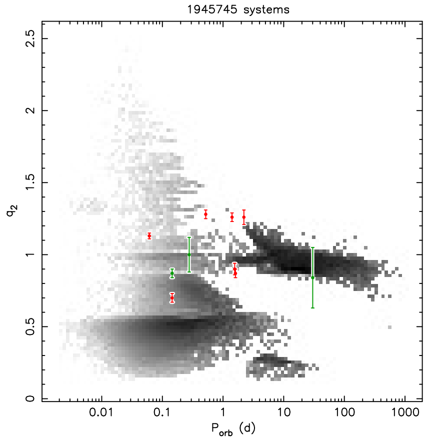
- $\alpha_{\rm CE} = 1.0$, λ: simple fit
- Constant MT conservation factor $0.0 \leq \beta \leq 1.0$

Match with observed systems

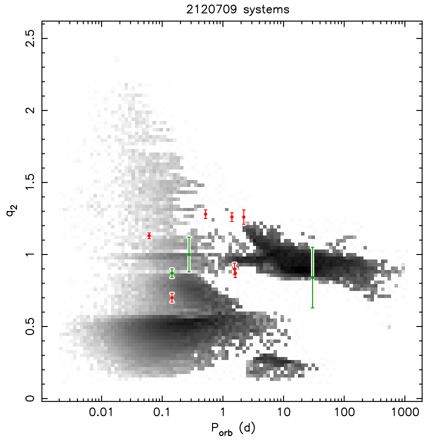
- M_2 within observed uncertainty ($\Delta\, M_{2,\rm min} = 0.05\,M_\odot$)
- q_2 within observed uncertainty
- $P_{\rm orb}$ within 1% from observed

Population synthesis: $q - P_{\rm orb}$

Conservative MT



Non-conservative MT

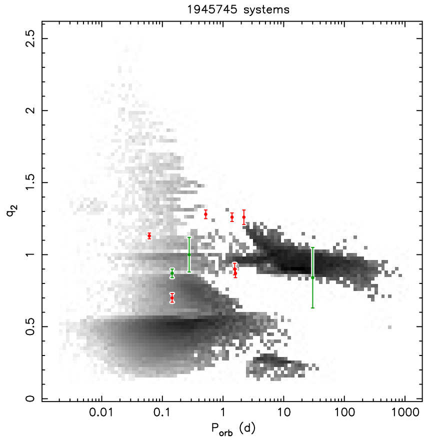


MvdS et al., in preparation

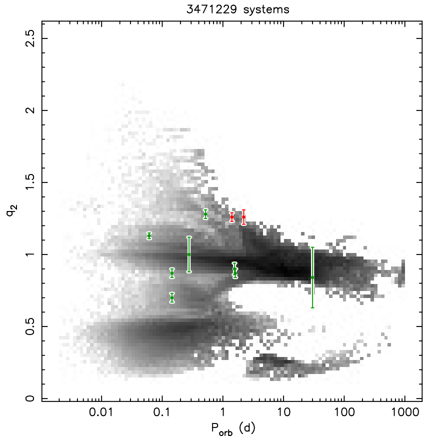
- $\beta = 0.0$–1.0
- standard stability criterion ($q_{\rm crit}$)

Population synthesis: $q - P_{\rm orb}$

Conservative MT



Non-conservative MT

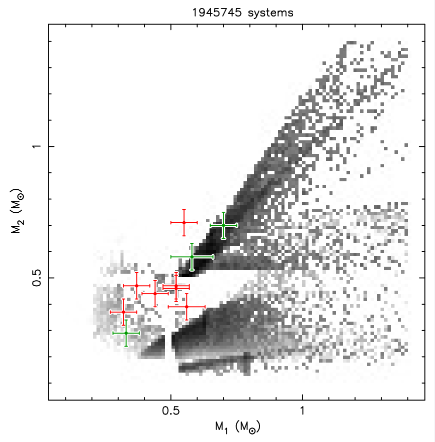


MvdS et al., in preparation

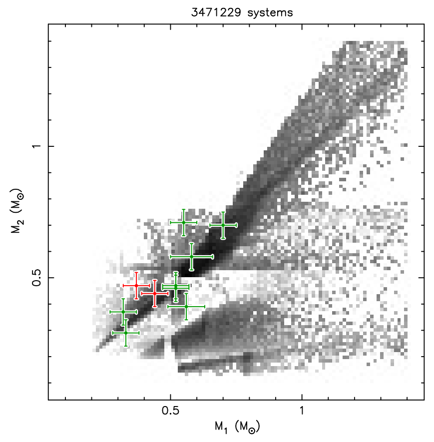
- $\beta = 0.0$–1.0
- adapted stability criterion ($q_{\rm crit} \to \zeta$s)

Population synthesis: individual masses

Conservative MT



Non-conservative MT



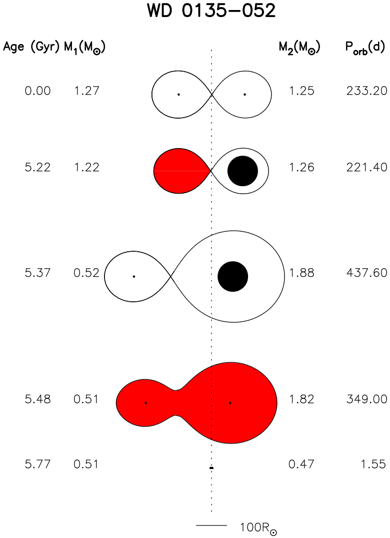
MvdS et al., in preparation

Match with observed double-lined double white dwarfs

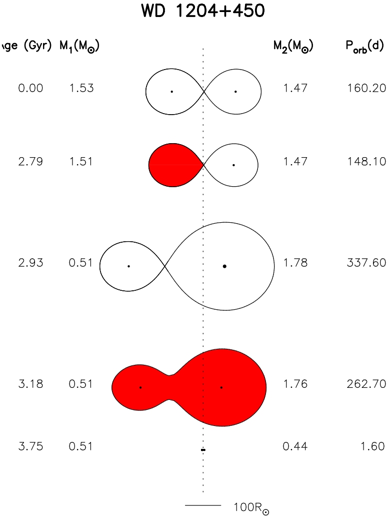
System	Observed				Reconstructed				Initial			
	M_1 ($M_\odot$)	M_2 ($M_\odot$)	q_2	P_{orb} (d)	M_1 ($M_\odot$)	M_2 ($M_\odot$)	q_2	P_{orb} (d)	M_{1i} ($M_\odot$)	M_{2i} ($M_\odot$)	P_i (d)	β_{max}
WD 0135	0.52	0.47	0.90	1.556	0.515	0.466	0.905	1.547	1.27	1.25	233	0.7
WD 0136	0.37	0.47	1.26	1.407	—	—	—	—	—	—	—	—
WD 0957	0.32	0.37	1.13	0.061	0.315	0.356	1.130	0.061	1.03	1.02	16.2	0.4
WD 1101	0.33	0.29	0.87	0.145	0.386	0.334	0.865	0.144	1.47	1.47	170	1.0
PG 1115	0.7	0.7	0.84	30.09	0.826	0.701	0.849	30.038	3.45	2.03	3452	1.0
WD 1204	0.52	0.46	0.87	1.603	0.515	0.443	0.860	1.598	1.53	1.47	160	0.3
WD 1349	0.44	0.44	1.26	2.209	—	—	—	—	—	—	—	—
HE 1414	0.55	0.71	1.28	0.518	0.534	0.694	1.300	0.519	1.93	1.86	60.3	0.2
WD 1704	0.56	0.39	0.70	0.145	0.520	0.357	0.687	0.145	1.96	1.88	31.0	0.0
HE 2209	0.58	0.58	1.00	0.277	0.582	0.580	0.997	0.277	2.45	2.45	352	1.0

See references in Maxted et al. (2002), Nelemans & Tout (2005) and MvdS et al. (2006)

Results: example solutions



$\beta = 0.7$

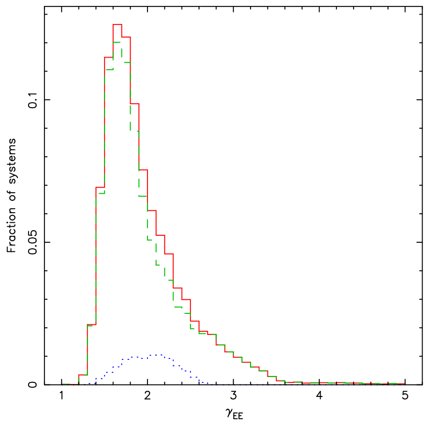


$\beta = 0.3$

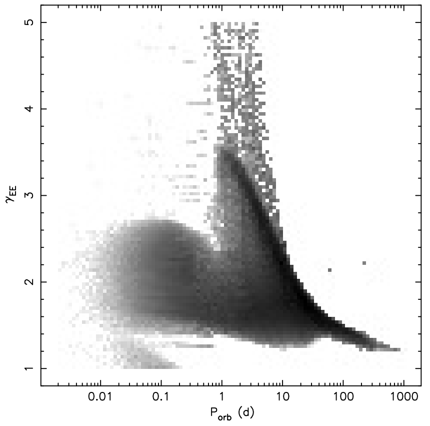
MvdS et al., in preparation rocheplot.sf.net

Population synthesis: γ-values for non-conservative MT

Non-conservative MT



Non-conservative MT



DWD conclusions

Stable, conservative mass transfer + CE

- Cannot explain the 10 observed DWDs
- Best try: 1–4 systems, with $\alpha_{\rm CE} \gtrsim 1.6$

Unstable envelope ejection (α, γ)

- Explains 9–10 out of 10 of them reasonably
- Explains 8–9 systems when cooling age is taken into account
- Physics is somewhat poor for γs

Stable, non-conservative mass transfer + CE

- Can explain $\sim 8/10$ observed DWDs reasonably well (q, $P_{\rm orb}$, M_1, M_2)
- Forms fewer DWDs through CE, but many more through stable MT
- Crux is adapted stability criterion, not AM loss
- Results effectively in $1.5 \lesssim \gamma \lesssim 2.0$ for many systems

Progenitors:

- Equal-mass systems in double CE (β independent)
- Near-equal-mass systems + small β

Work in progress

Observable?

- Convert population of physical binaries into detectable double-lined systems (Alberto)
- Take into account cooling ages

Interpretation

- Why should $\beta \ll 1$?
- Connection with near-equal-mass initial systems?

More observations

- Single-lined systems
- ELMs systems

End. . .