Formation of double white dwarfs and AM CVn stars

Marc van der Sluys[1,2]

Frank Verbunt[1], Onno Pols[1]
[1]Utrecht University, The Netherlands

Mike Politano[3], Chris Deloye[2], Ron Taam[2], Bart Willems[2]
[2]Northwestern University, Evanston, IL, USA; [3]Marquette University, Milwaukee, WI, USA

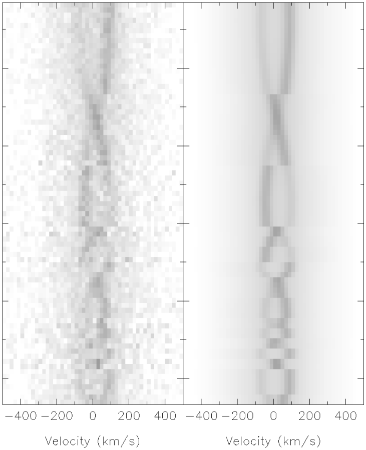
AM CVn workshop, Cape Town, September 2, 2008

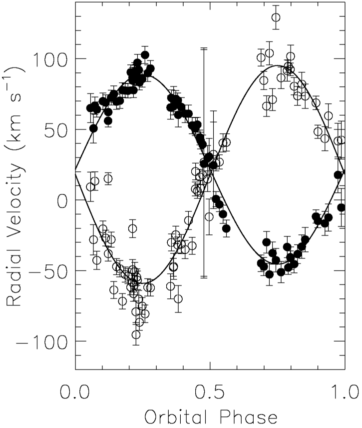
NORTHWESTERN UNIVERSITY

Outline

1. **Common envelopes**
   - Observed double white dwarfs
   - Common-envelope evolution
   - Envelope ejection
2. **Progenitor models**
   - Single-star models
3. **Reverse evolution**
   - Second mass-transfer phase
   - Stable first mass-transfer phase
   - Envelope ejection as first mass transfer
4. **Future work**

Observed double white dwarfs





WD 0316+768, Adapted from Maxted et al., 2002

NORTHWESTERN UNIVERSITY

Observed double white dwarfs

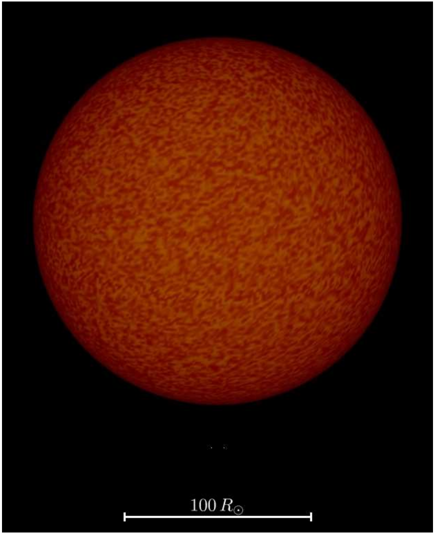
System	P_{orb} (d)	a_{orb} ($R_\odot$)	M_1 ($M_\odot$)	M_2 ($M_\odot$)	q_2 (M_2/M_1)	$\Delta\tau$ (Myr)
WD 0135–052	1.556	5.63	0.52 ± 0.05	0.47 ± 0.05	0.90 ± 0.04	350
WD 0136+768	1.407	4.99	0.37	0.47	1.26 ± 0.03	450
WD 0957–666	0.061	0.58	0.32	0.37	1.13 ± 0.02	325
WD 1101+364	0.145	0.99	0.33	0.29	0.87 ± 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

See references in: Maxted et al., 2002 and Nelemans & Tout, 2005.

NORTHWESTERN UNIVERSITY

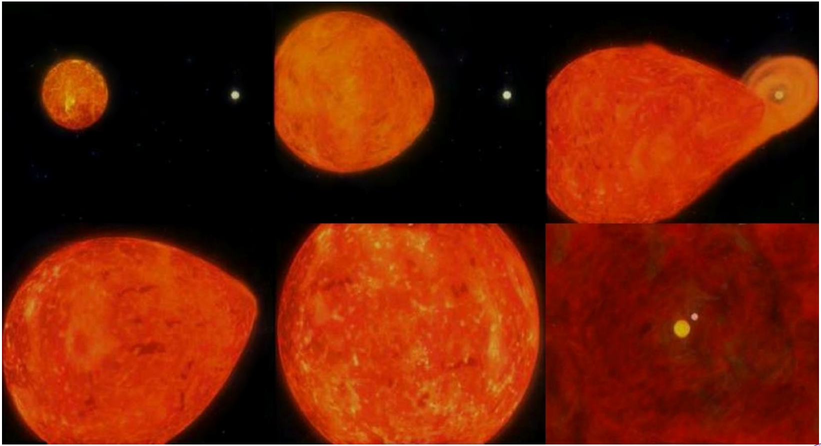
Common envelope



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

NORTHWESTERN UNIVERSITY

Common envelope



NORTHWESTERN UNIVERSITY

Envelope ejection

- Classical α-common envelope (spiral-in):
  - orbital energy is used to expel envelope (Webbink, 1984):

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

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

- γ-envelope ejection (EE, spiral-in not necessary):
  - envelope ejection with angular-momentum balance (Nelemans et al., 2000):

$$\frac{J_{\rm i} - J_{\rm f}}{J_{\rm i}} = \gamma_{\rm CE} \frac{M_{\rm 1i} - M_{\rm 1f}}{M_{\rm 1i} + M_2}$$

  - $\gamma_{\rm CE} \approx 1.5$ is the efficiency parameter

Envelope ejection

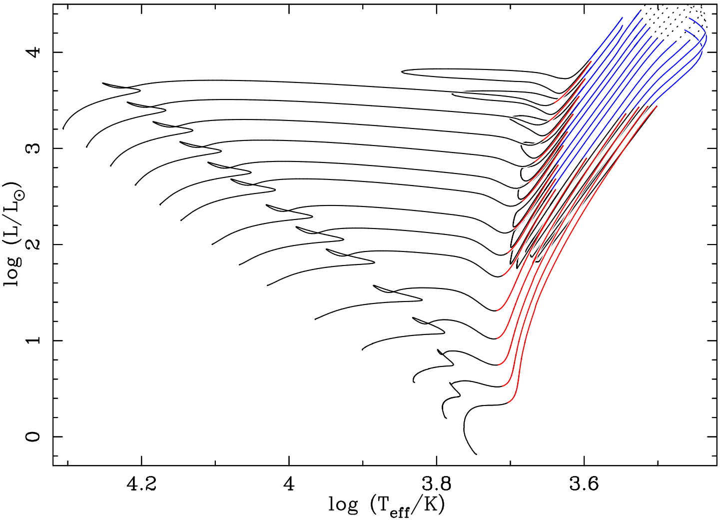
Assumption:

- Envelope ejection occurs much faster than nuclear evolution, hence:
  - core mass does not grow during envelope ejection
  - no accretion by companion during envelope ejection

From Eggleton models:

- White-dwarf mass fixes evolutionary state of progenitor
- Giant radius determines orbital period of progenitor
- Envelope binding energy dictates what α_{CE} is needed

Progenitor models



Eggleton code

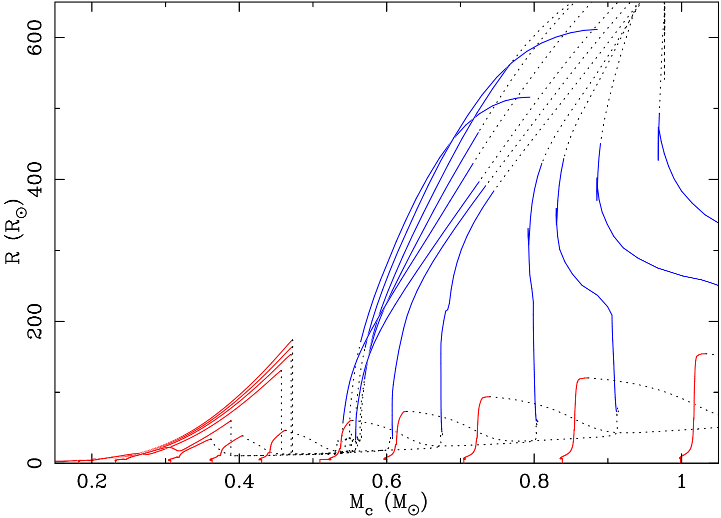
199 singe-star models

0.8-10 $M_\odot$

RGB

AGB

Progenitor models



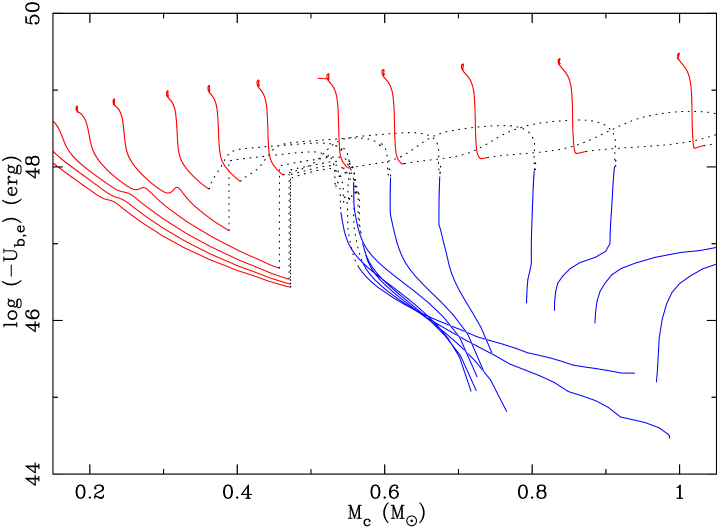
R_* provides P_{orb} at onset of EE

RGB

AGB

NORTHWESTERN UNIVERSITY

Progenitor models



Envelope U_{bind} provides α_{CE}

RGB

AGB

Evolutionary scenarios

Stable + unstable

MS + MS

↓ Stable M.T. (cons.) ↓

WD + MS

↓ Unstable M.T. (α-CE) ↓

WD + WD

Unstable + unstable

MS + MS

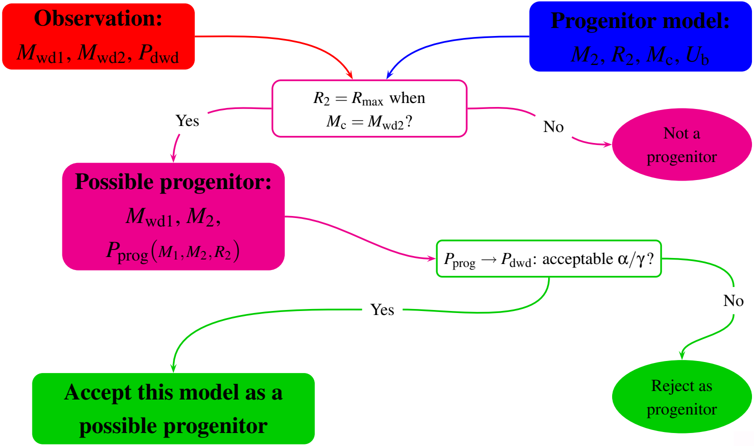
↓ Unstable M.T. (γ-EE) ↓

WD + MS

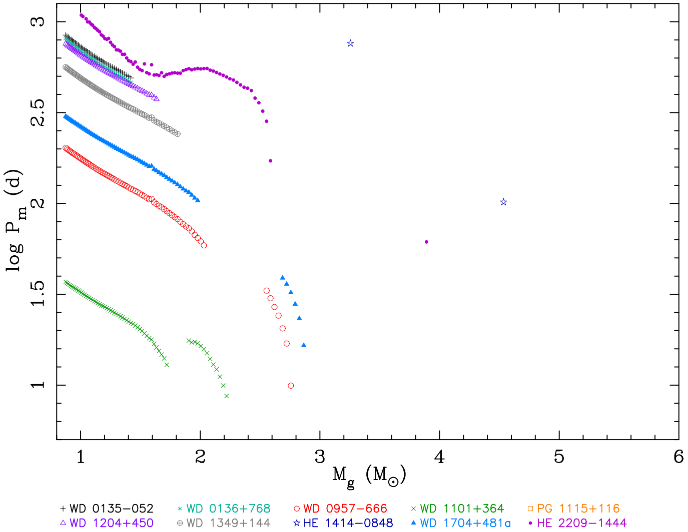
↓ Unstable M.T. (α, γ-EE) ↓

WD + WD

Confusogram



α-CE results

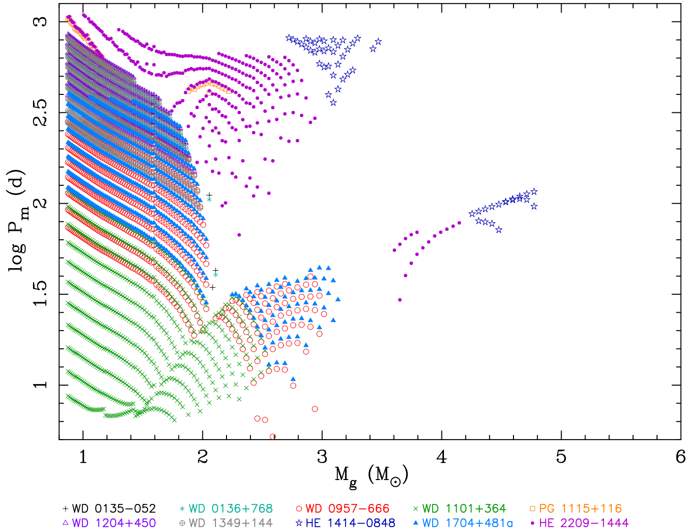


Accept cases with:
$0.1 < \alpha_{ce} < 10$

Assume no errors in observed masses

NORTHWESTERN UNIVERSITY

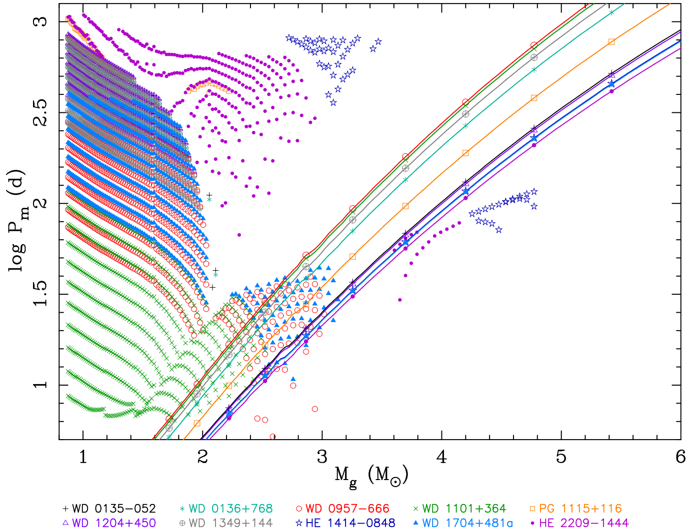
α-CE results



Accept cases with: $0.1 < \alpha_{ce} < 10$

Introduce errors in observed masses: $\pm 0.05\, M_\odot$

Conservative first mass transfer



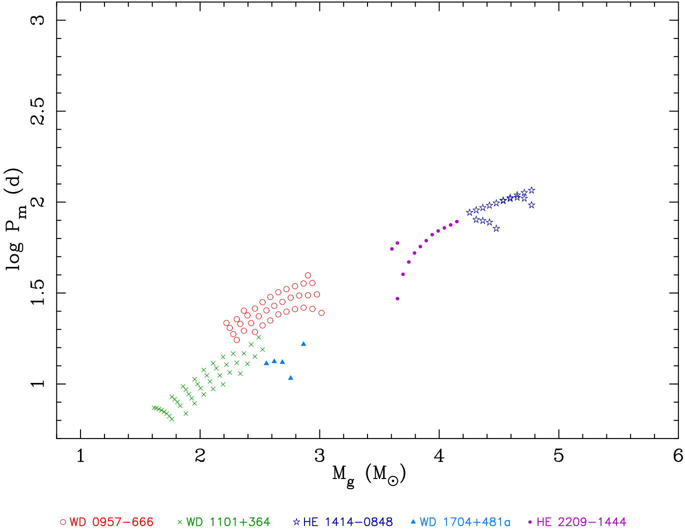
Maximum P_{orb} after stable mass transfer with $q_i = 0.62$

(Nelemans et al., 2000)

Only 5 systems have CE solutions with $P_{orb} < P_{max}$

NORTHWESTERN UNIVERSITY

Conservative first mass transfer

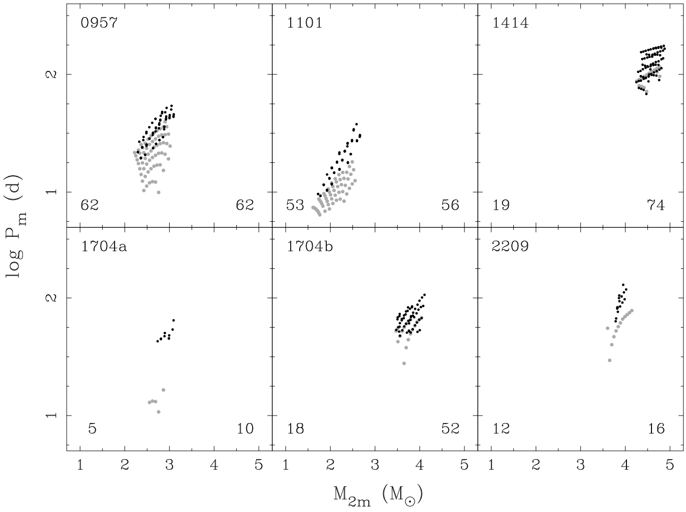


CE solutions that may be formed by stable mass transfer

Conservative mass transfer: M_{tot} and J_{orb} fixed

One free parameter: q_i

Conservative mass transfer: M, P



570 binary models, computed to match pre-CE systems

spiral-in

stable

Results:

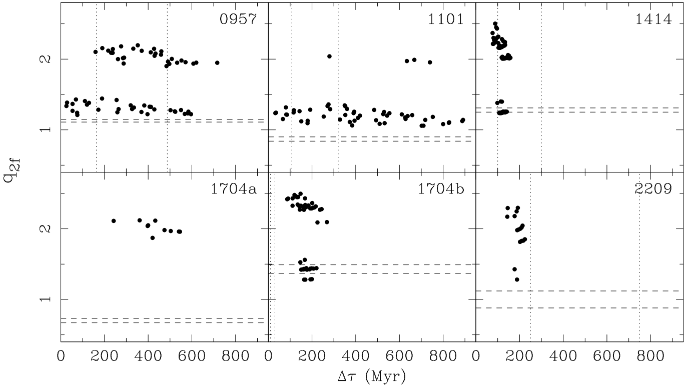
39% dynamical

18% contact

43% DWD

NORTHWESTERN UNIVERSITY

Conservative mass transfer: q, Δt



1414 fits

0957, 1101, 1704b and **2209** nearly fit

Out of ten systems, 1 can be explained, 4 are close

Conclusions

Conservative MT:

- More accurate models change α-CE only slightly
- After stable mass transfer, white-dwarf primaries have too low mass and too long orbital periods
- We can reproduce perhaps 1–4 out of 10 systems, all with $\alpha_{\rm ce} > 1.6$
- **Conservative mass transfer cannot explain the observed double white dwarfs**

Angular-momentum balance

- Average specific angular momentum of the system:

$$\frac{J_\mathrm{i} - J_\mathrm{f}}{J_\mathrm{i}} = \gamma_\mathrm{s} \frac{M_{1\mathrm{i}} - M_{1\mathrm{f}}}{M_{\mathrm{tot,i}}}$$

- Specific angular momentum of the accretor:

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

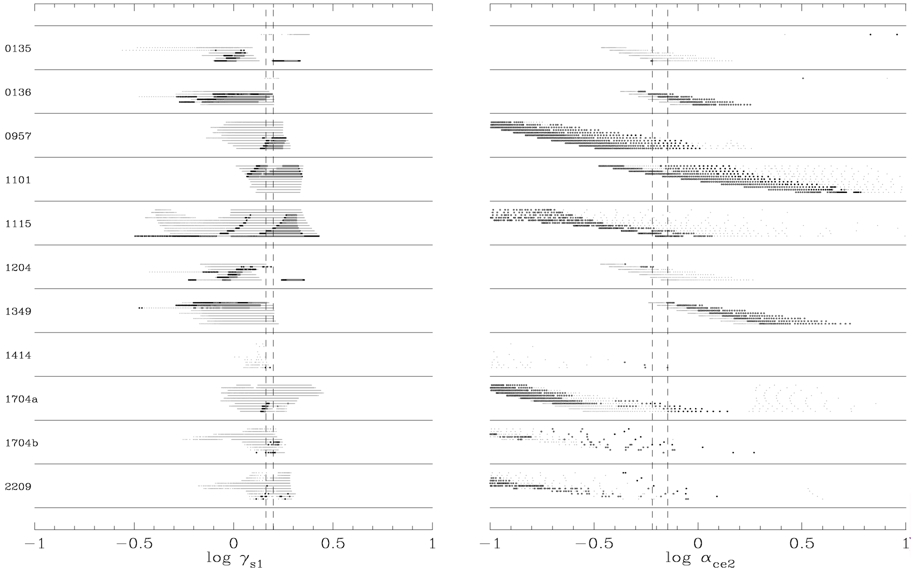
- Specific angular momentum of the donor:

$$\frac{J_\mathrm{i} - J_\mathrm{f}}{J_\mathrm{i}} = \gamma_\mathrm{d} \frac{M_{1\mathrm{i}} - M_{1\mathrm{f}}}{M_{\mathrm{tot,f}}} \frac{M_{2\mathrm{i}}}{M_{1\mathrm{i}}}$$

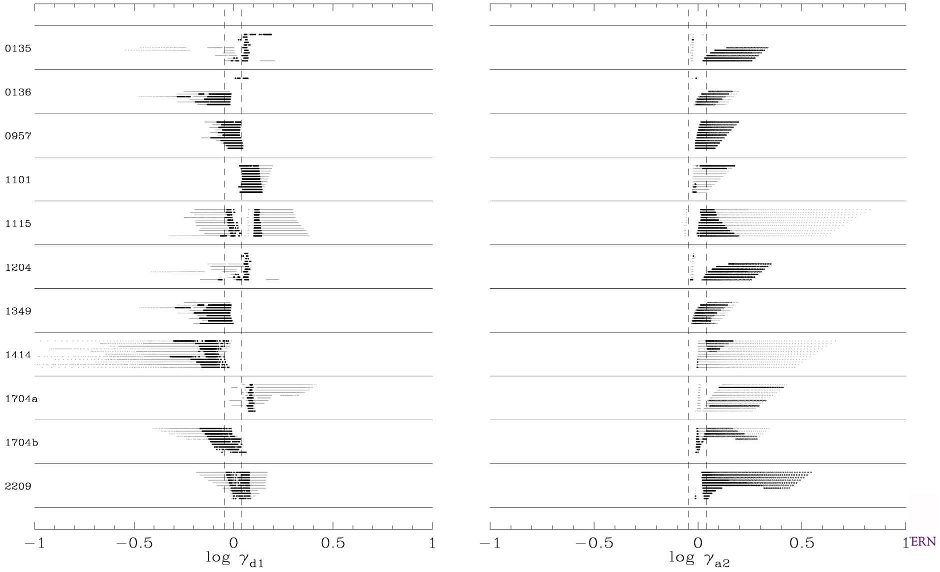
Models

- Number of progenitor models:
  - 10+1 observed systems
  - 199 progenitor models in our grid
  - 11 variations in observed mass: $-0.05, -0.04, ..., +0.05\ M_\odot$
  - total: $11 \times 11 \times \sum_{n=1}^{198} n \approx$ 2.4 million
- Filters:
  - dynamical MT: $R_* > R_\mathrm{BGB}$ and $q > q_\mathrm{crit}$
  - age: $\tau_1 < \tau_2 < 13\,\mathrm{Gyr}$
  - EE-parameter: $0.1 < \alpha_\mathrm{ce}, \gamma < 10$
- Candidate progenitors left: $\sim$ 204 000

Results for $\gamma_s + \alpha_{ce}$



Results for $\gamma_d + \gamma_a$



Results: overview

Select systems with:

- $0.8 < \alpha_{ce} < 1.2$
- $1.46 < \gamma_s < 1.79$
- $0.9 < \gamma_{a,d} < 1.1$

System	1: $\gamma_s\alpha_{ce}$	2: $\gamma_s\gamma_s$	3: $\gamma_a\alpha_{ce}$	4: $\gamma_a\gamma_a$	5: $\gamma_d\alpha_{ce}$	6: $\gamma_d\gamma_a$	Best:
0135	−	+	+	−	+	+	2,3,5,6
0136	+	+	+	+	+	+	1–6
0957	+	+	−	+	+	+	1,2,4,5,6
1101	+	+	+	−	+	+	1,2,3,5,6
1115	+	+	+	+	+	+	1–6
1204	−	+	+	+	+	+	2–6
1349	+	+	+	+	+	+	1–6
1414	−	+	−	+	−	+	2,4,6
1704a	+	+	−	−	−	−	1,2
1704b	+	+	−	+	+	+	1,2,4,5,6
2209	+	+	−	−	+	+	1,2,5,6

+: α, γ within range, −: α, γ outside range

NORTHWESTERN UNIVERSITY

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

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

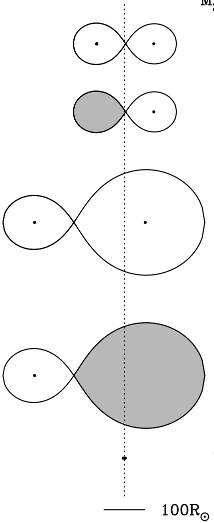
$+$: $\Delta(\Delta t) < 50\%$, $\sim$: $50\% < \Delta(\Delta t) < 500\%$, $-$: $\Delta(\Delta t) > 500\%$

NORTHWESTERN UNIVERSITY

Results: example solution

WD 0136+768

	Age (Gyr)	$M_1(M_\odot)$	$M_2(M_\odot)$	P_{orb}(d)
	0.000	1.70	1.59	106.10
$\gamma_d = 0.96 \rightarrow$	1.940	1.70	1.59	106.10
	1.940	0.37	1.59	371.40
$\gamma_a = 1.05 \rightarrow$	2.390	0.37	1.59	371.40
$\Delta\tau = 450\,\mathrm{Myr} \rightarrow$	2.540	0.37	0.46	1.41



Results: solutions

WD	Mthd.	γ_1	γ_2, α_{ce2}	$\Delta\tau$/Myr obs	mdl	M_{1i} $M_\odot$	M_{2i} $M_\odot$	P_i d	P_m d	M_{1f} $M_\odot$	M_{2f} $M_\odot$	P_f d
0135	$\gamma_d\gamma_a$	1.11	0.94	350	118	3.30	2.90	36.28	41.10	0.47	0.42	1.56
0136	$\gamma_d\gamma_a$	0.96	1.05	450	450	1.70	1.59	106.1	371.4	0.37	0.46	1.41
0957	$\gamma_d\gamma_a$	1.00	1.01	325	317	1.98	1.83	26.17	79.26	0.33	0.37	0.06
1101	$\gamma_d\gamma_a$	1.10	0.98	215	322	2.87	2.34	22.02	28.23	0.39	0.34	0.14
1115	$\gamma_d\gamma_a$	0.97	1.04	160	240	5.42	3.42	201.2	1012.	0.89	0.75	30.09
1204	$\gamma_d\gamma_a$	1.09	0.92	80	100	3.34	2.98	15.47	19.99	0.47	0.41	1.60
1349	$\gamma_d\gamma_a$	0.95	0.98	0	101	1.86	1.81	63.44	241.2	0.35	0.44	2.21
1414	$\gamma_d\gamma_a$	0.95	0.99	200	188	3.51	3.09	70.81	358.3	0.52	0.66	0.52
1704a	$\gamma_d\gamma_a$	1.11	1.13	-20	52	2.06	1.88	40.37	65.66	0.51	0.36	0.14
1704b	$\gamma_d\alpha_{ce}$	1.03	0.15	20	182	1.68	1.65	212.1	478.6	0.41	0.58	0.14
2209	$\gamma_d\gamma_a$	1.04	1.05	500	340	4.15	2.94	98.45	294.3	0.63	0.63	0.28

Conclusions

- Conservative mass transfer cannot explain the observed double white dwarfs
- Unstable envelope ejection can do this
- Several EE descriptions can reconstruct observed masses and periods
- $\gamma_s\gamma_s$ and $\gamma_d\gamma_a$ can in addition explain most observed cooling-age differences

Future work

Population-synthesis code

- Based on grid of single-star models with Eggleton code
- Models provide M_{c}, R, U_{bind}
- Stellar wind, tidal coupling included
- Used for modelling binary mergers due to CE spiral-in (Politano et al., 2008)
- Second common-envelope phase implemented to study formation of double white dwarfs
- Need to:
  - include naked helium-star models
  - include more physics, *e.g.* magnetic braking

Future work

Purpose:

- Study effect of *e.g.*:
  - different α/γ-prescriptions
  - wind mass loss
  - angular-momentum loss
- on formation of *e.g.*:
  - double white dwarfs
  - He star/white dwarf binaries
  - AM CVns
  - CVs