Population synthesis of common-envelope mergers on the giant branches

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Outline

Stellar mergers

Occurrence:

- Collisions: $\tau \sim \mathrm{day}$? (Sills et al. 2001)
- Binary mergers: convective envelope: $\tau \sim \tau_{\mathrm{dyn}}; \mathrm{yr} - \mathrm{kyr}$?
- Binary mergers: radiative envelope: $\tau \sim \tau_{\mathrm{th}} \to \tau_{\mathrm{dyn}}$

HST

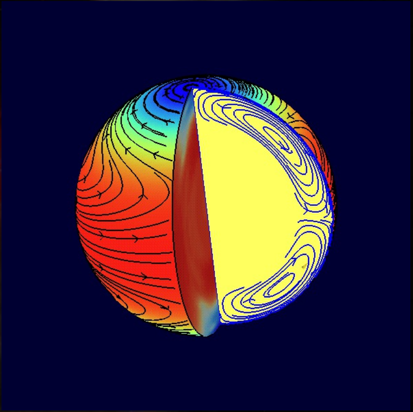
NOAO/AURA/NSF

- A significant fraction of stars ($\sim 10\%$?) may be involved in mergers
- Luminous red novae?
- V 838 Mon?

Merger products

Physics:

- **Angular momentum !**
- Rapid, differential rotation
- Enhanced mixing
- Magnetic fields
- Enhanced mass loss



Stanford, SOHO

Merger products

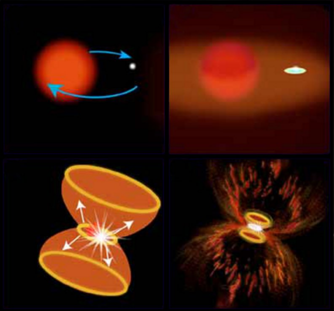
Physics:

- **Angular momentum !**
- Rapid, differential rotation
- Enhanced mixing
- Magnetic fields
- **Enhanced mass loss**

Merger products

Observability:

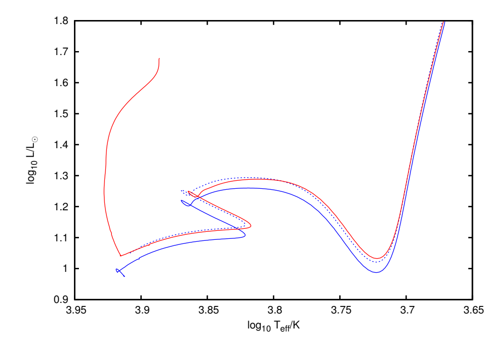
- Rapid rotation?
- Abundance anomalies?
- Circumstellar material
- Blue stragglers
- Cluster dynamics



HST

- “Weird” binaries
- B[e] stars?
- Hot subdwarfs?
- Asymmetric PNe
- IMBHs?

Detailed collisions



$1.75\ M_\odot$: Collision product Normal star
(dashes): Fully mixed model

Glebbeek & Pols, 2008

Use:

- 1D stellar models
- collide them in hydro
- bring remnant in hydrostatic equilibrium
- evolve in 1D
- for low-mass stars: "Entropy" "sorting"

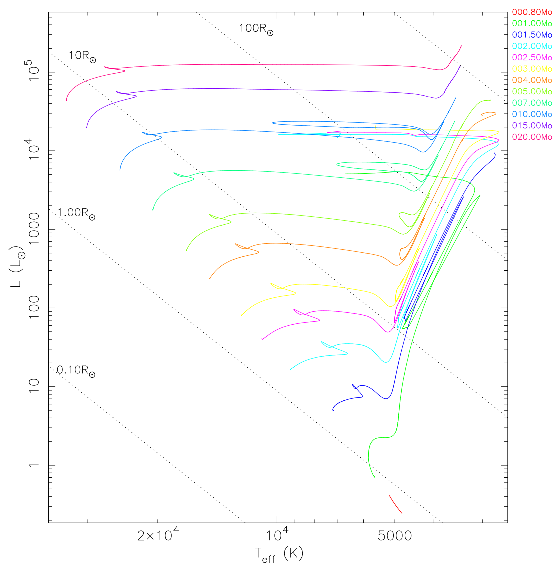
Differences in:

- Timescales
- Luminosities
- Core masses
- Mixing

Input models

Stellar-evolution code ev (Eggleton, 1971,2, etc.):

- 116: single-star models: 0.5, 0.6, . . . , 10.0, 10.5, . . . , 20.0 $M_\odot$ (primary, merger remnant)
- 28 brown-dwarf models: 0.01 – 0.60 $M_\odot$ (secondary)
- Solar composition; X=0.70, Y=0.28, Z=0.02



Input models

Stellar-evolution code `ev`:

- Core mass: $M_\mathrm{c} \equiv$ central region where $X < 0.1$
- Envelope binding energy: $E_\mathrm{bind} \equiv \int_{M_\mathrm{c}}^{M_\mathrm{s}} \left(E_\mathrm{int}(m) - \frac{Gm}{r(m)} \right) \mathrm{d}m$

- Convective mixing: $l/H_P = 2.0$
- Overshooting: none for $M < 1.2\,M_\odot$, $\delta_\mathrm{ov} = 0.12$ for $M \geq 1.2\,M_\odot$
- Stellar wind: "Reimers" (1975), De Jager et al. (1988)
- *Helium-flash-avoidance routine* `FGB2HB`

Treatment of evolution

Stars

- Constant star-formation rate
- Randomly select 10^7 binaries:
  - $M_{\rm p}$: Miller-Scalo IMF
  - $q \equiv M_{\rm s}/M_{\rm p}$:
    $g(q)\,{\rm d}q = \{q^{-0.9}, 1, q\}\,{\rm d}q$
- Follow the evolution of track closest in mass to primary
- When mass comes closer to next track, jump with conservation of $M_{\rm c}$

Treatment of evolution

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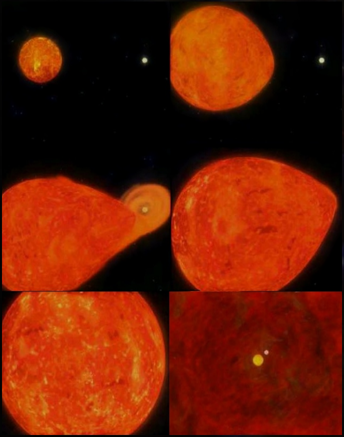
Treatment of evolution

Orbit

- Assume synchronous rotation on RGB, AGB: $\omega_{\rm p} = \omega_{\rm orb}$
- Mass and AM loss from stellar wind
- If $v_{\rm rot} > v_{\rm crit}$: lose additional mass and AM until $v_{\rm rot} \leq v_{\rm crit}$
- Redistribute AM, so that $J_{\rm tot} = (I_{\rm p} + I_{\rm orb})\,\omega_{\rm orb}$
- $v_{\rm crit} \equiv \{0.1, 1/3, 1.0\}\, v_{\rm br}$

Common envelope and spiral-in



- CE occurs when:
  - $R_\mathrm{p} > R_\mathrm{RL,p}$ and $q > q_\mathrm{crit}(M_\mathrm{p}, M_\mathrm{c})$ (Hurley et al. 2002)
  - $J_\mathrm{prim} > \frac{1}{3} J_\mathrm{orb}$ (Darwin 1879)
- Classical energy formalism to determine post-CE orbit (Webbink 1984):

$$E_\mathrm{bind} = \alpha_\mathrm{CE} \left(\frac{G M_\mathrm{p} M_\mathrm{s}}{2\, a_\mathrm{i}} - \frac{G M_\mathrm{c} M_\mathrm{s}}{2\, a_\mathrm{f}} \right)$$

- $\alpha_\mathrm{CE} = \{0.1, 0.5, 1.0\}$
- Merger occurs if after CE: $R_\mathrm{RL,s} < R_\mathrm{s}$

Merger process

The merger product has:

- the core mass of the original primary
- the maximum mass for which:
  - the star is spinning (sub-)critically ($v_{\rm rot} \leq v_{\rm crit}$)
  - $M_{\rm mrg} \leq M_{\rm p} + M_{\rm s}$
- the evolutionary state of the primary, or later

In addition,

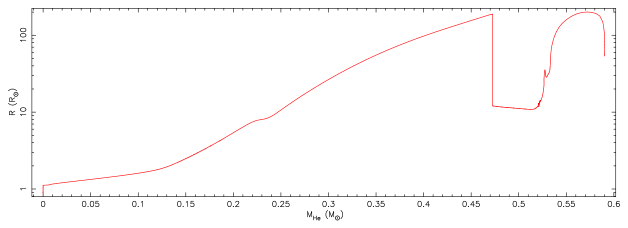
- the surplus mass from the binary does not interact with the star (accretion, tides)

Evolution of the merger product

After the merger:

- the merger product evolves mostly in the same way as a normal single star
  - *e.g.* L, R, etc. are identical to those for a star with the same M, $M_{\rm c}$
  - difference: $v_{\rm rot}$, hence $\dot{M}$

- whenever $v_{\rm rot} \geq v_{\rm crit}$, the star undergoes enhanced mass loss, to ensure that it remains spinning sub-critically
  - this is especially important around core helium ignition

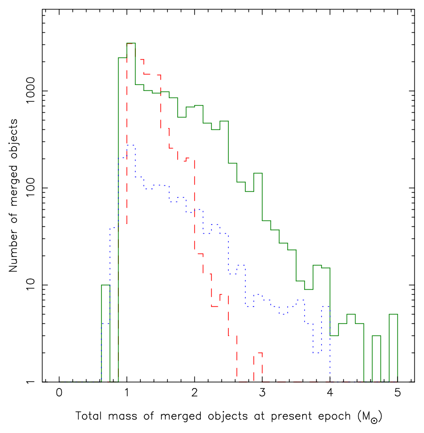


Population-synthesis results

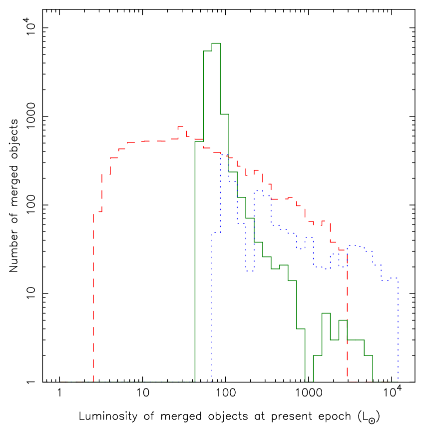
	Number	Fraction of previous group	Fraction of initial population
Total binary population:	**10,000,000**	**100%**	**100%**
No MT	7,094,523	71%	71%
Stable MT	1,267,854	13%	13%
Unstable MT:	**1,637,623**	**16%**	**16%**
CE Survivors:	789,807	48%	7.9%
Mergers:	**847,816**	**52%**	**8.5%**
Mergers due to RLOF	689,815	81%	6.9%
Mergers due to tidal capture	158,001	19%	1.6%
Mergers on RGB	738,385	87%	7.4%
Mergers on AGB	109,431	13%	1.1%
WDs	822,773	97%	8.2%
GB/HB stars:	**25,041**	**3%**	**0.25%**
RGB	**9,301**	**37%**	**0.09%**
HB	**14,305**	**57%**	**0.14%**
AGB	**1,435**	**6%**	**0.01%**
Critically rotating RGB stars	297	3.2%	0.003%
Critically rotating HB stars	4,504	31%	0.05%
Critically rotating AGB stars	1	0.1%	0.00001%

Merger properties

Total mass:



Luminosity:

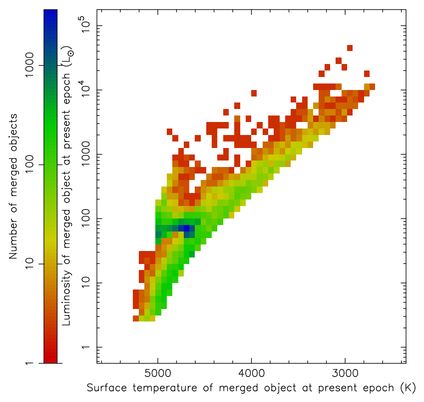


RGB HB AGB

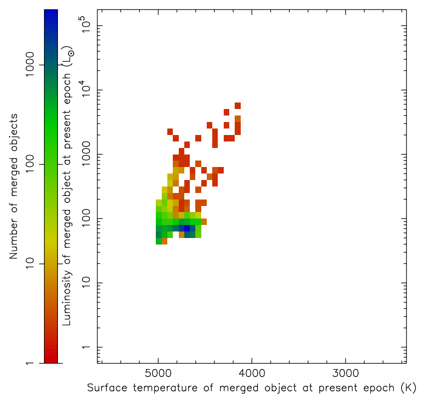
$$v_{\rm crit} = \frac{1}{3} v_{\rm br}$$

Merger population

All merger products:



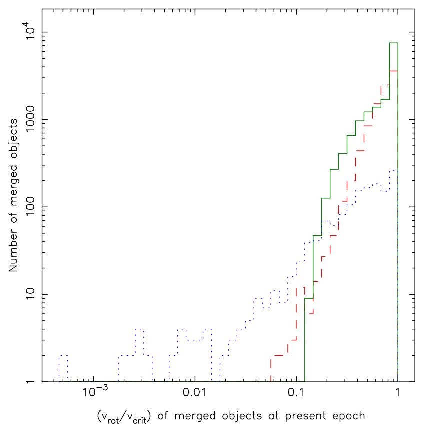
Merger products on HB:



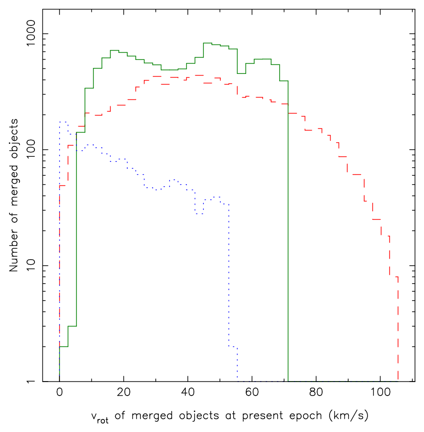
$$v_{\rm crit} = \frac{1}{3} v_{\rm br}$$

Rotational velocities

v_{rot}/v_{crit}:



v_{rot} (km/s):



$$v_{crit} = \frac{1}{3} v_{br}$$

Rotational velocities

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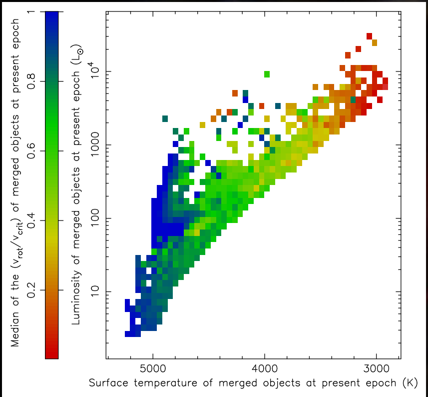
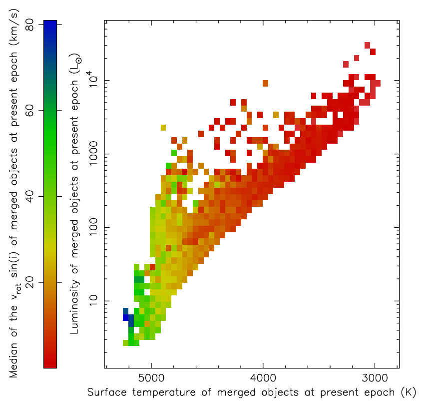


$v_{rot} \sin i$ (km/s):



$$v_{crit} = \frac{1}{3} v_{br}$$

Sub-populations

Population	N	$\frac{N}{N_{tot}}$	M ($M_\odot$)	v sin i (km/s)	Fraction with $v_{rot} \leq 0.1\, v_{crit}$	Fraction with $v_{rot} = v_{crit}$	M_{rej} ($M_\odot$)	$\frac{M_{rej}}{M_{bin}}$	$\frac{\Delta M_{mrg}}{M_{mrg,i}}$
RGB	9301	0.37	1.20	18.4	(0.001)	0.0319	0.63	0.34	0.00
HB	14305	0.57	1.35	16.1	(0.0000)	0.3149	0.93	0.40	0.12
AGB	1435	0.06	1.34	6.0	0.0683	(0.0007)	0.94	0.42	0.13
Total	25041	1.00	1.28	16.2	0.0043	0.1918	0.81	0.38	0.07

Dependence on input parameters

Model	N	$\frac{N_{RGB}}{N_{tot}}$	M ($M_\odot$)	v sin i (km/s)	Fraction with $v_{rot} \leq 0.1\, v_{crit}$	Fraction with $v_{rot} = v_{crit}$	M_{rej} ($M_\odot$)	$\frac{M_{rej}}{M_{bin}}$	$\frac{\Delta M_{mrg}}{M_{mrg,i}}$
α_{CE} = 0.1	32882	0.29	1.23	16.5	0.0054	0.2726	0.83	0.40	0.10
α_{CE} = 0.5	28269	0.34	1.23	16.2	0.0048	0.2201	0.81	0.38	0.08
α_{CE} = 1.0	25041	0.37	1.28	16.2	0.0043	0.1918	0.81	0.38	0.07

Common-envelope parameter

- for a *larger* α_{CE}, a smaller fraction of all CEs leads to merger
- for a *smaller* α_{CE}, wider binaries can merge
  - merger remnants have more angular momentum

Dependence on input parameters

Model	**N**	$\frac{N_{RGB}}{N_{tot}}$	**M** ($M_\odot$)	**v sin i** (km/s)	**Fraction with** $v_{rot} \leq$ 0.1 v_{crit}	**Fraction with** $v_{rot} =$ v_{crit}	M_{rej} ($M_\odot$)	$\frac{M_{rej}}{M_{bin}}$	$\frac{\Delta M_{mrg}}{M_{mrg,i}}$
$g(q) = q^{-0.9}$	25343	0.35	1.29	16.3	0.0045	0.2012	0.28	0.18	0.07
$g(q) = 1$	25041	0.37	1.28	16.2	0.0043	0.1918	0.81	0.38	0.07
$g(q) = q$	24853	0.36	1.29	16.0	0.0049	0.2015	1.10	0.46	0.07

Initial-mass-ratio distribution

- $g(q) = q$ favours equal-mass binaries, $g(q) = q^{-0.9}$ favours extreme mass ratios
- For $g(q) = q$, secondary masses are larger and more mass is rejected during the merger

Dependence on input parameters

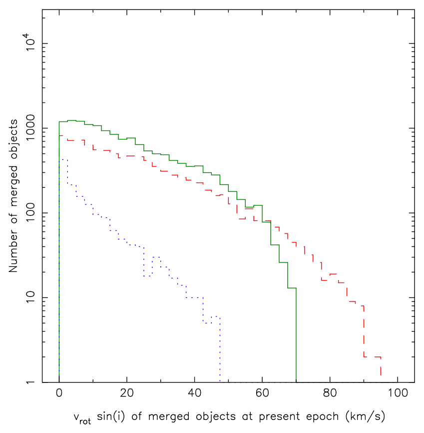
Model	N	$\frac{N_{RGB}}{N_{tot}}$	M ($M_\odot$)	v sin i (km/s)	Fraction with $v_{rot} \leq 0.1\, v_{crit}$	Fraction with $v_{rot} = v_{crit}$	M_{rej} ($M_\odot$)	$\frac{M_{rej}}{M_{bin}}$	$\frac{\Delta M_{mrg}}{M_{mrg,i}}$
$v_{crit} = 0.1\, v_{br}$	25490	0.38	1.20	4.6	0.0058	0.1974	0.90	0.41	0.08
$v_{crit} = \frac{1}{3}\, v_{br}$	25041	0.37	1.28	16.2	0.0043	0.1918	0.81	0.38	0.07
$v_{crit} = v_{br}$	24414	0.33	1.46	47.7	0.0051	0.1343	0.63	0.30	0.02

Critical rotational velocity

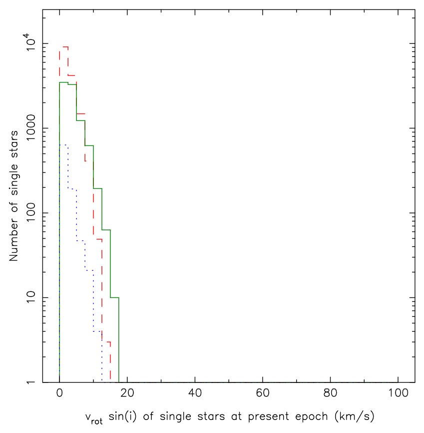
- The observed (projected) rotational velocity scales with our definition of v_{crit}
- For smaller v_{crit}, more mass is ejected during and after merger

Comparison to single stars

Merger remnants:



Single stars:



RGB HB AGB

$$v_{\mathrm{crit}} = \frac{1}{3} v_{\mathrm{br}}$$

Comparison to single stars

Ev. phase	population	N	$\frac{N}{N_{tot}}$	M ($M_\odot$)	v sin i (km/s)	Fraction with $v_{rot} \leq 0.1\, v_{crit}$	Fraction with $v_{rot} = v_{crit}$
RGB	mergers	9301	0.37	1.20	18.4	(0.001)	0.0319
	single	178651	0.61	1.20	1.9	0.9627	0.000
HB	mergers	14305	0.57	1.35	16.1	(0.0000)	0.3149
	single	104979	0.36	1.58	3.2	0.0886	0.0021
AGB	mergers	1435	0.06	1.34	6.0	0.0683	(0.0007)
	single	10487	0.04	1.45	1.3	0.5657	(0.0000)
Total	mergers	25041	1.00	1.28	16.2	0.0043	0.1918
	single	294117	1.00	1.23	2.3	0.6366	0.0008

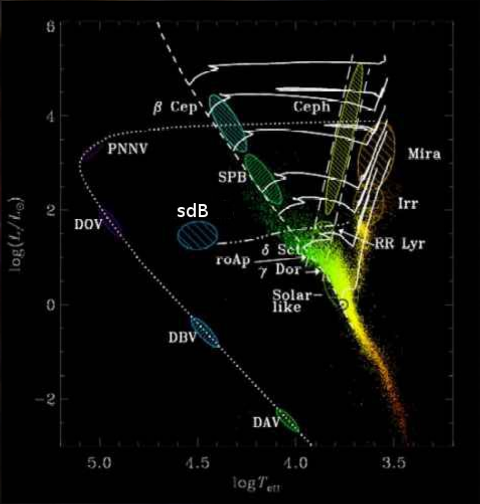
Critical rotational velocity

- The observed (projected) rotational velocity is roughly an order of magnitude larger for merger products
- Most merger products on the GBs have ignited helium, most normal single stars have not

sdB stars

Basic properties:

- Core helium burning stars with very thin ($\lesssim 0.02\,M_\odot$) hydrogen-rich envelope
- In the field $\sim$ 40–70% are found in binaries
- In GCs mostly observed as **single** sdB stars
- Masses observed $\sim 0.39\,M_\odot - 0.7\,M_\odot$ (*e.g.* asteroseismology)



sdB stars

Possible formation channels:

In wide binaries:

- One or two phases of stable Roche-lobe overflow

In close binaries:

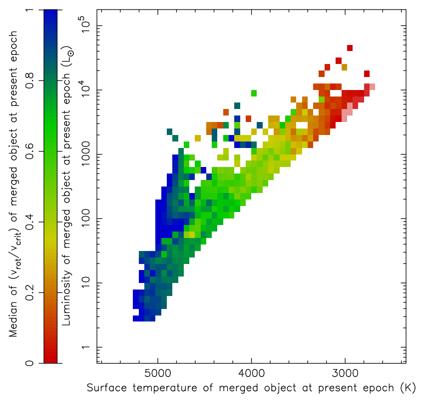
- One or two CE/spiral-in phases

Single sdB stars:

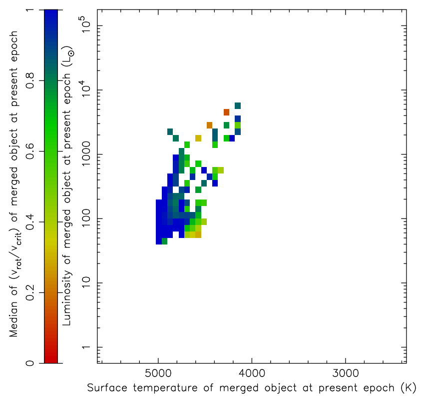
- He-WD–He-WD mergers ($M \gtrsim 0.4\,M_\odot$)
- Strong mass loss at tip of RGB (*e.g.* capture of planet; Soker & Harpaz, 2000, 2007; Livio & Siess, 1999a,b)
- **CE merger on the RGB** (Soker 1998, Soker & Harpaz 2000, 2007)

Rotational velocities for merged HB stars

All merger products:



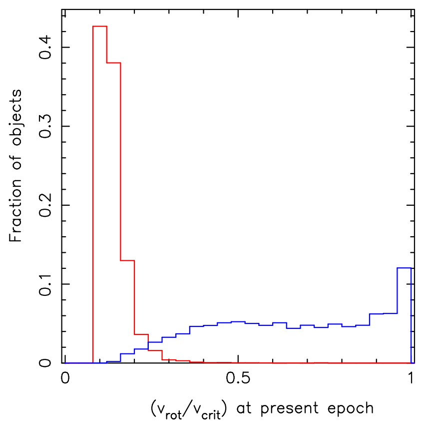
Merger products on HB:



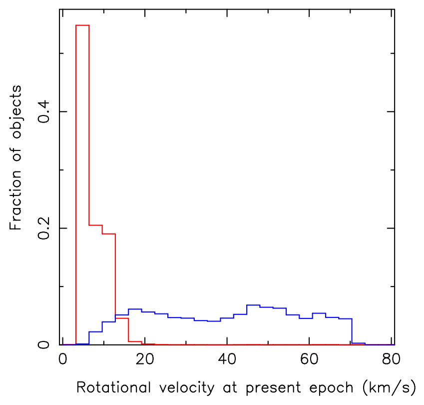
$$v_{\rm crit} = \frac{1}{3} v_{\rm br}$$

Rotational velocities

$\mathbf{v}_{\rm rot}/\mathbf{v}_{\rm crit}$:



$\mathbf{v}_{\rm rot}(\mathbf{km/s})$:

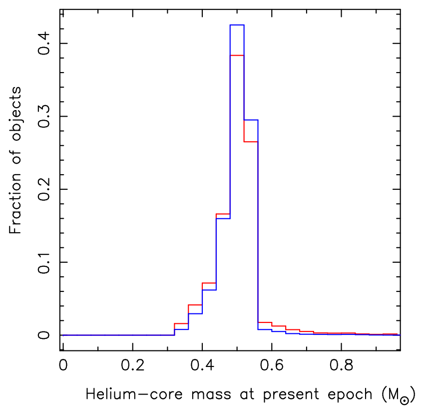


Merger products **Single stars**

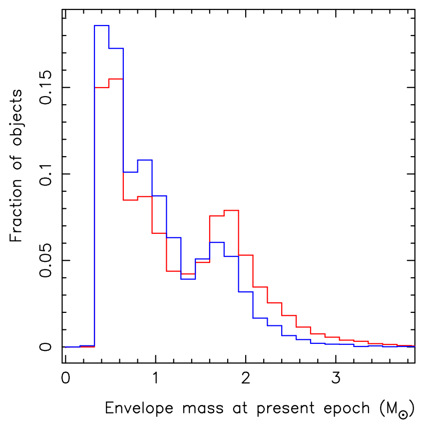
$$v_{\rm crit} = \frac{1}{3} v_{\rm br}$$

Core and envelope masses

Helium-core masses:



Envelope masses:

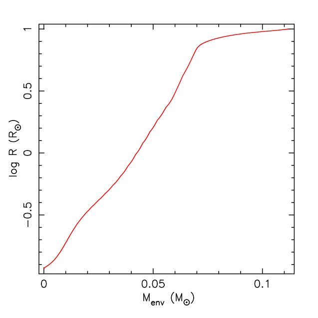


Merger products **Single stars**

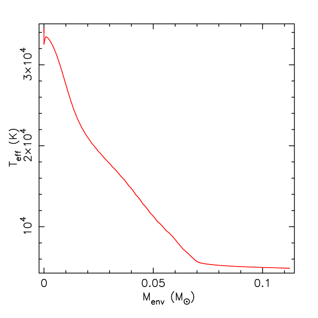
Losing the envelope

Detailed model of an HB star with initial parameters $M \approx 0.59\,M_\odot$, $M_{env} \approx 0.11\,M_\odot$ and $v_{rot} \approx 25\,km/s$:

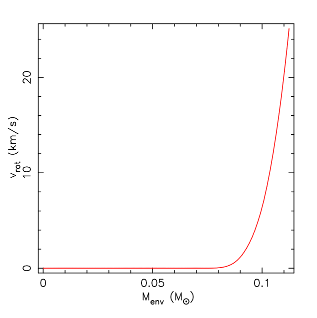
M_{env} vs. $\log R$:



M_{env} vs. T_{eff}:



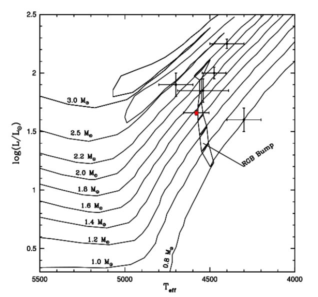
M_{env} vs. v_{rot}:

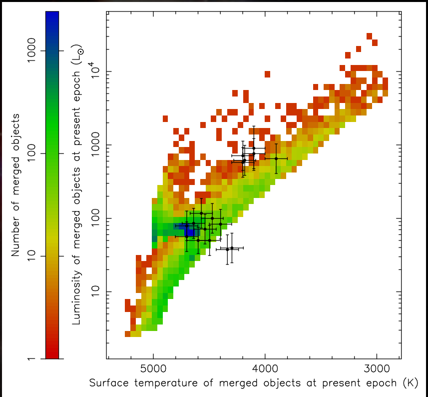


Lithium-rich giants

Reddy & Lambert 2005; Kumar & Reddy 2009:

Star	[Fe/H]	$T_{\rm eff}$	$M_\star/M_\odot$	$\log L/L_\odot$	$\log \epsilon(\mathrm{Li})$	$^{12}\mathrm{C}/^{13}\mathrm{C}$
HD 77361	-0.02 ± 0.1	4580 ± 75	1.5 ± 0.2	1.66 ± 0.1	3.82 ± 0.10	4.3 ± 0.5
HD 233517	-0.37	4475 ± 70	1.7 ± 0.2	2.0^{a}	4.22 ± 0.11	...
IRAS 13539−4153	-0.13	4300 ± 100	0.8 ± 0.7	1.60^{a}	4.05 ± 0.15	20
HD 9746	-0.06	4400 ± 100	1.92 ± 0.3	2.02	3.75 ± 0.16	28 ± 4
HD 19745	-0.05	4700 ± 100	2.2 ± 0.6	1.90^{a}	3.70 ± 0.30	16 ± 2
IRAS 13313−5838	-0.09	4540 ± 150	1.1	1.85^{a}	3.3 ± 0.20	12 ± 2

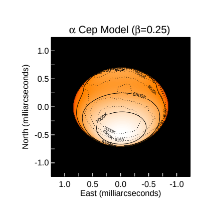




Oblateness

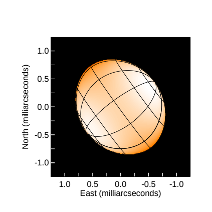
Zhao et al. 2009

α Cep



$e = 0.60$

α Oph

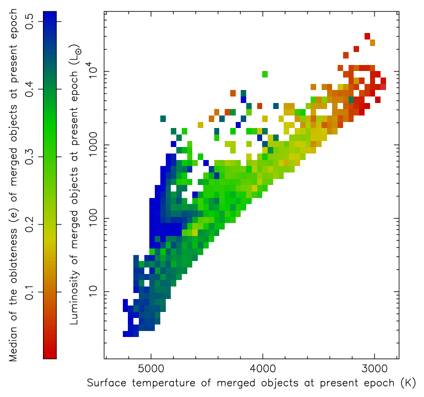


$e = 0.55$

$$e \equiv \sqrt{1 - \left(R_{\rm pol}/R_{\rm eq}\right)^2}$$

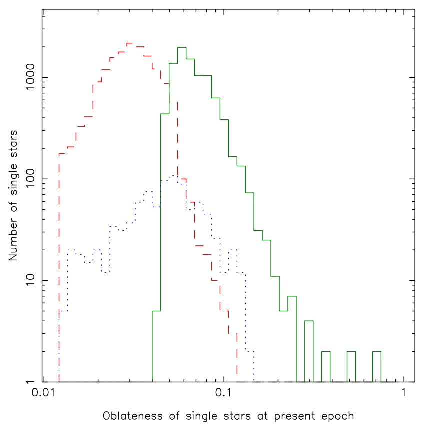
MacLaurin spheroids (1742):

$$\frac{\omega}{\sqrt{2\pi G\rho}} = \sqrt{\frac{\sqrt{1-e^2}}{e^3}\left(3-2e^2\right)\mathrm{asin}(e) - \frac{3}{e^2}\left(1-e^2\right)}$$

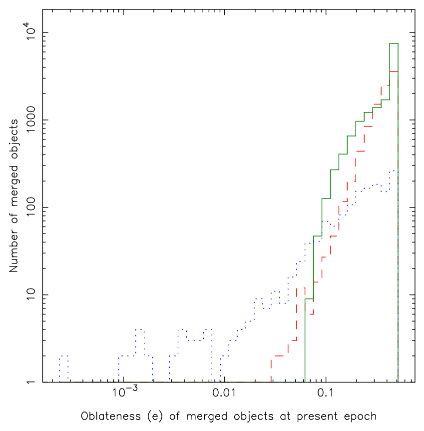


Oblateness

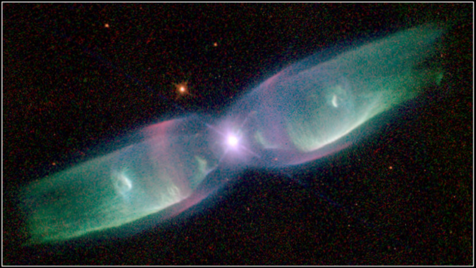
Single stars



Merger products



Asymmetric planetary nebulae?



Planetary Nebula M2-9 HST • WFPC2
PRC97-38a • ST ScI OPO • December 17, 1997
B. Balick (University of Washington) and NASA

Butterfly nebula (HST)

Conclusions

Population-synthesis code:

- We produced an initial version of a code with which we can study large populations of merger remnants, albeit with simplified assumptions

Results:

- Common-envelope mergers on the giant branches lead to rapidly rotating merger products
- Merger products through this channel rotate roughly $10\times$ faster than normal single stars
- Roughly 60% of merger products have ignited helium; $\sim$ 40% of normal single stars have not
- In a population with 50% initial binaries, $\sim$ 3.4% of the single stars would be a GB merger remnant

Conclusions

sdB stars:

- Contraction of a merger product due to helium ignition provides a natural way to create rapidly rotating HB stars
- A small fraction of these HB stars have thin envelopes; these stars are close to becoming single sdB stars

Other observables:

- Telltales of (former) rapid rotation may include abundance anomalies, small envelope mass, oblate stars, IR excess and asymmetric nebulae

Future work

To-do list

- Use more flexible implementation for mass loss due to winds and rotation
- Include magnetic braking for merger product
- Look for mechanism to remove last bit of HB-star envelope (perhaps on RGB?)
- Combine population synthesis and “entropy” “sorting”:
  - do population synthesis to get the mergers
  - use entropy sorting to get a merger product
  - interpolate to create an evolution model
  - evolve it with a detailed stellar-evolution code (including rotation)

The End