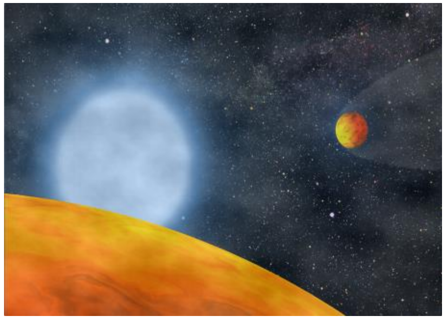
High-precision tests of stellar physics from high-precision photometry

SpS13-XXVIII IAU GA



The formation of sdB stars

vvv

Influence of substellar bodies on late stages of stellar evolution

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I. Substellar companions for sdB stars

Introduction to sdB stars

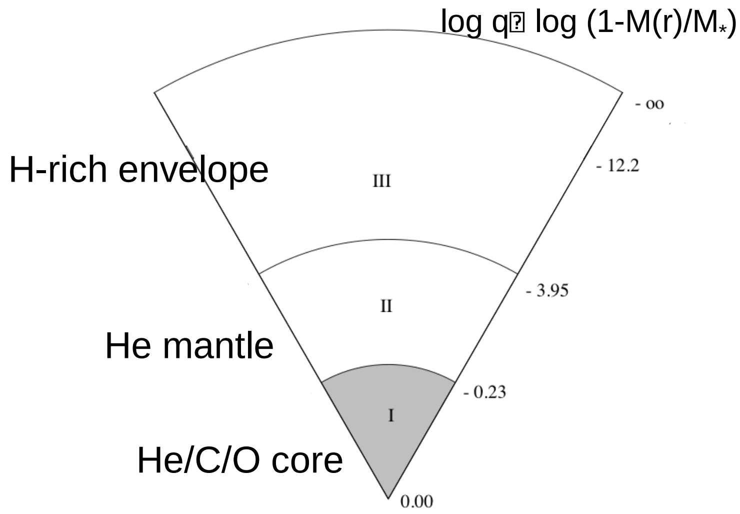
Hot (T_{eff} = 20 000 - 40 000 K) and compact (log g = 5.2 - 6.2) stars belonging to Extreme Horizontal Branch (EHB)

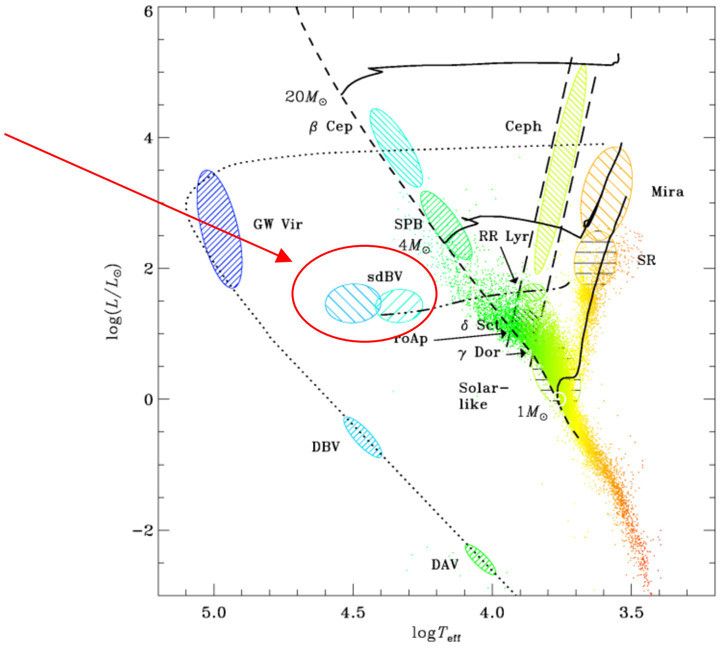
- convective He-burning core (I), radiative He mantle (II) and very thin H-rich envelope (III)
- ~50% of sdB stars reside in binary systems, generally in close orbit ($P_{orb} \leq$ 10 days)

Two classes of multi-periodic sdB pulsators (V~14-15):

> short-periods (P ~ 80 - 600 s), A ≤ 1%, p-modes (envelope)

> long-periods (P ~ 45 min - 2 h), A ≤ 0.1%, g-modes (core). Space observations required !

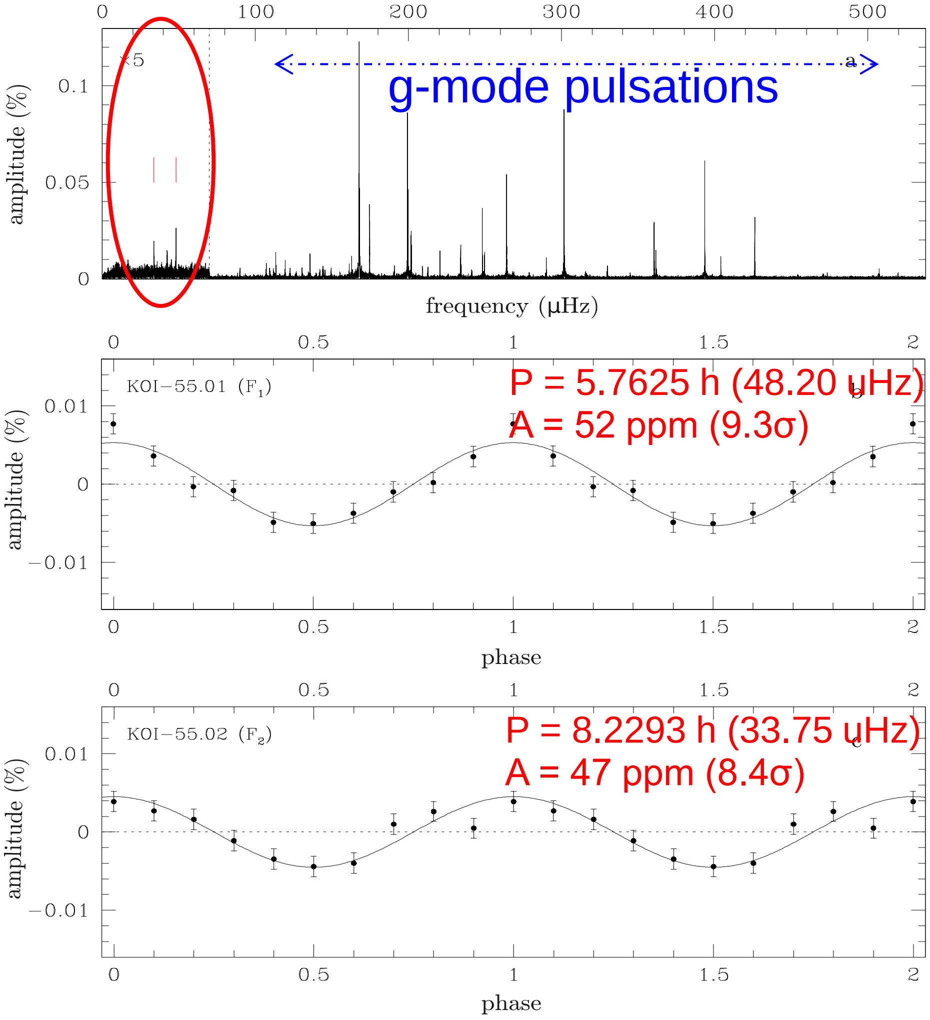




Substellar companions for sdB stars

KPD 1943+4058 aka KOI55, a pulsating sdB star observed by *Kepler*

Q2+Q5-Q8: 14 months of Kepler data (spanning 21 months)



g-mode pulsations

P = 5.7625 h (48.20 μHz)
A = 52 ppm (9.3σ)

P = 8.2293 h (33.75 μHz)
A = 47 ppm (8.4σ)

From asteroseismology
(Van Grootel et al. 2010):

V = 14.87 , Distance = 1180 pc

M = 0.496 Ms, R = 0.203 Rs

T_{eff} = 27 730K, log g = 5.52

Age since ZAEHB ~ 18 Myr

Two intriguing periodic and coherent brightness variations are found at low frequencies, with tiny amplitudes

Charpinet et al., Nature, 480, 491

Substellar companions for sdB stars

Possible interpretations for these modulations:

- ✓ Stellar pulsations? → rejected (beyond period cutoff)
- ✓ Modulations of stellar origin: spots? → rejected (pulsations: star rotation ~ 39 d)
- ✓ Contamination from a fainter nearby star? → rejected based on pixel data analysis
- ✓ **Modulations of orbital origin**

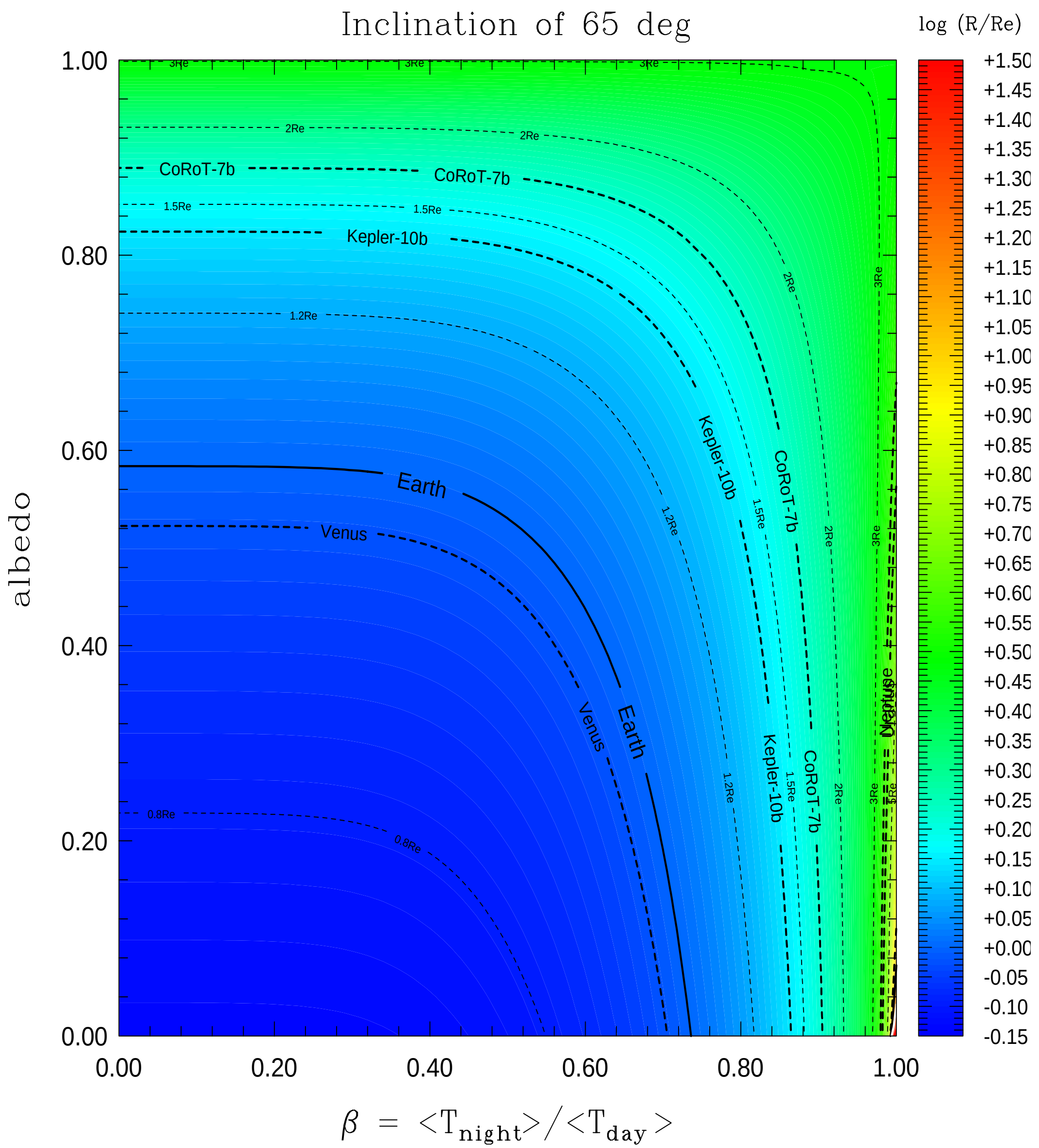
What sizes should these objects have to produce the observed variations?

Two effects: light reflection + thermal re-emission, both modulated along the orbit

$$R_j = \left(\frac{A_j}{\sin i}\right)^{\frac{1}{2}} \left(\frac{\alpha_j}{8a_j^2} + \frac{1}{2R_*^2}\frac{F_R(T_j) - F_R(\beta T_j)}{F_R(T_*)}\right)^{-\frac{1}{2}}$$

(see details in Nature paper, supplementary information)

Substellar companions for sdB stars



- From pulsations: i ~ 65°
- Assuming orbits aligned with equatorial plane
- Most relevant parameter range: low values for the albedo and β (day/night temp. contrast)

We have:

- Two Earth-size planets
- Orbiting very close (0.006 and 0.008 AU) to their host star
- Extremely hot (evaporating?)
- Orbiting an **evolved, core He-burning** star

How can we explain this?

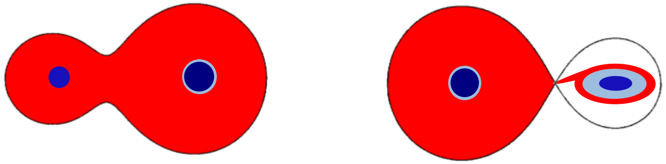
II. The formation of sdB stars: the theory

The formation of sdB stars

sdB stars are He-core burning stars with only a tiny H-rich envelope left

How such stars form is a long standing problem

- **For sdB in binaries (~50%)**



in the red giant phase: Common envelope ejection (CE), stable mass transfer by Roche lobe overflow (RLOF)

↓

The red giant lose its envelope at tip of RGB, when He-burning ignites (He flash)

↓

Remains the stripped core of the former red giant, which is the sdB star, with a stellar companion

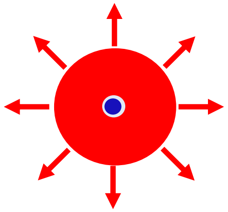
- **For single sdB stars (~50%)**

2 main scenarios:

1. Single star evolution:

enhanced mass loss at tip of RGB, at He-burning ignition (He-flash)

mechanism quite unclear (cf later)



2. The merger scenario:

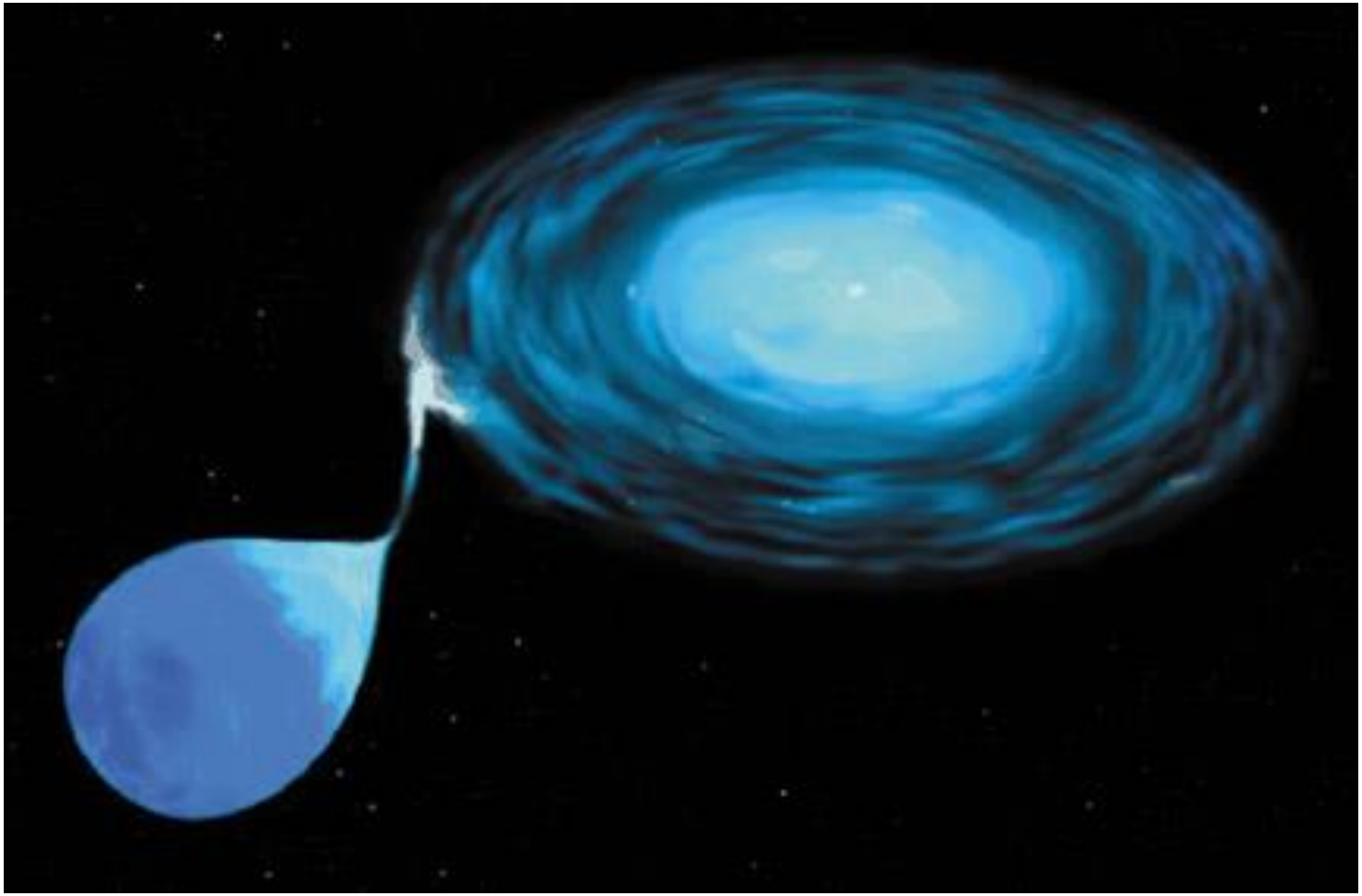
Two low mass helium white dwarfs merge to form a He core burning sdB star

Common envelope evolution (close binary sdB systems)

CEE: sdB + MS star or white dwarf

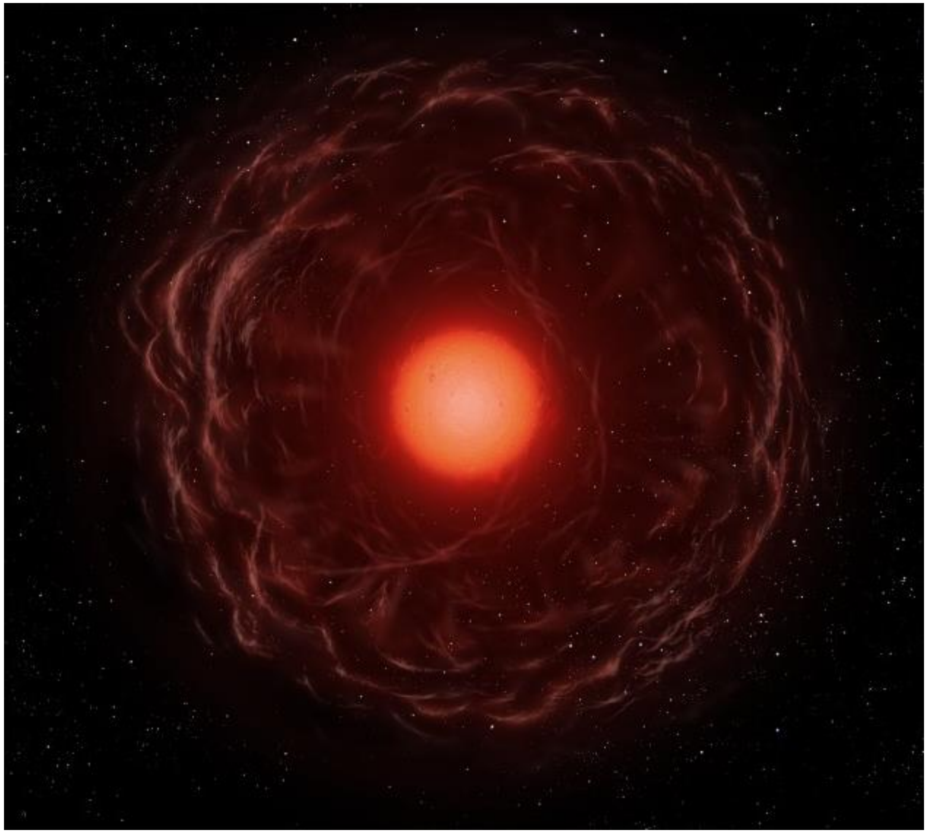
Stable Roche lobe overflow (wide binary sdB systems)

RLOF: sdB + MS star (later than F-G)



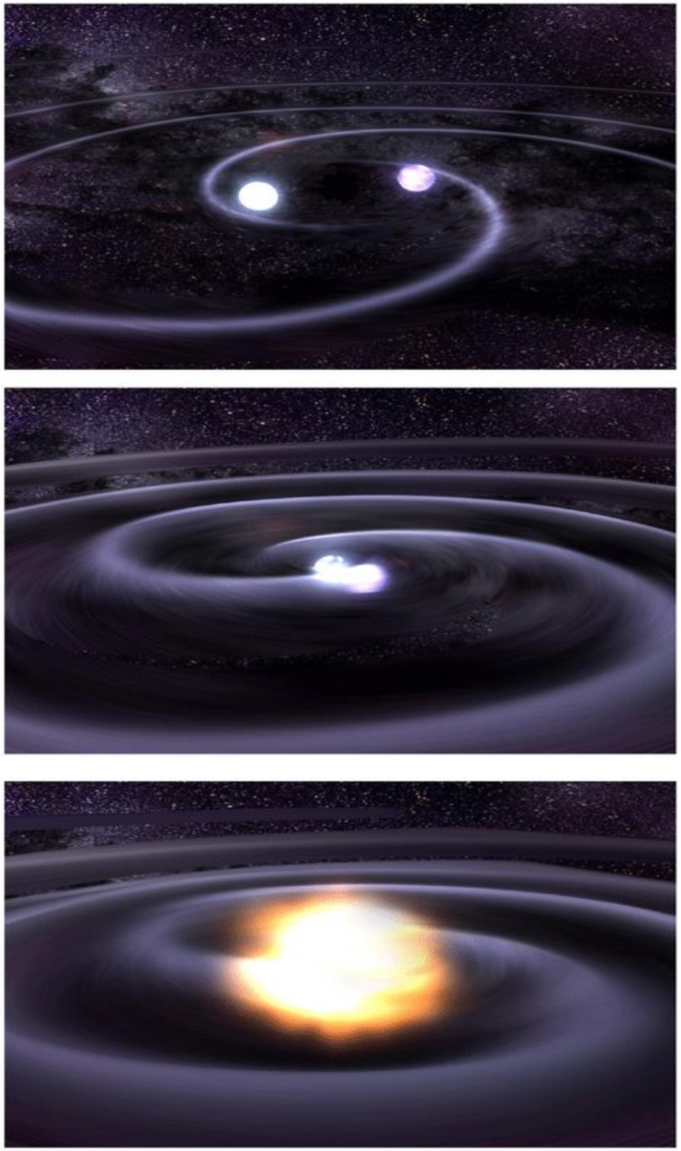
Single sdBs: single star evolution or He-white dwarfs mergers

Envelope ejection at tip of RGB

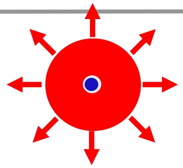


or

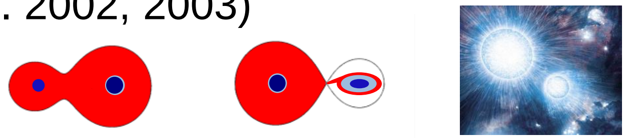
mergers

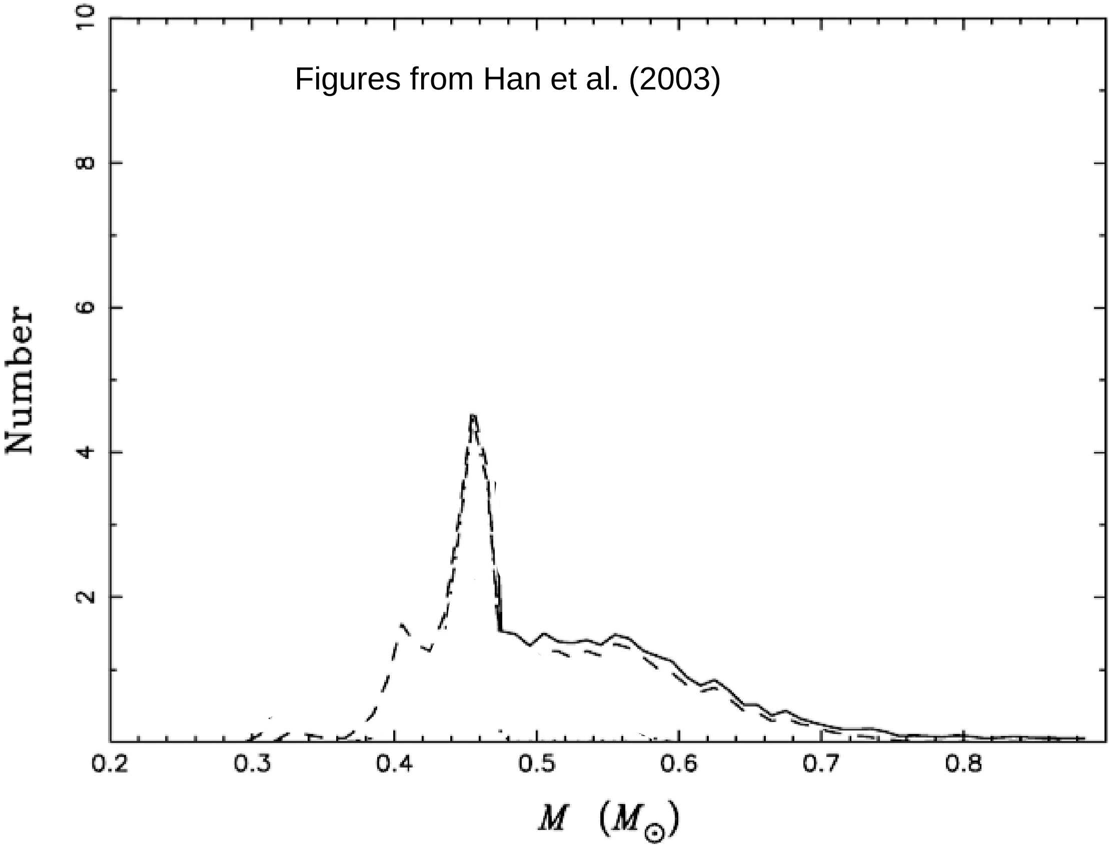


The formation of sdB stars: theoretical mass distributions



- Single star evolution: Mass range in 0.40 - 0.43 ≤ M_*/M_s ≤ 0.52 (Dorman et al. 1993)
- Binary star evolution: numerical simulations on binary population synthesis (Han et al. 2002, 2003)





Figures from Han et al. (2003)

Weighted mean distribution for binary evolution:

(including selection effects)

0.30 ≤ M_*/M_s ≤ 0.70

peak ~ 0.46 Ms (CE, RLOF)

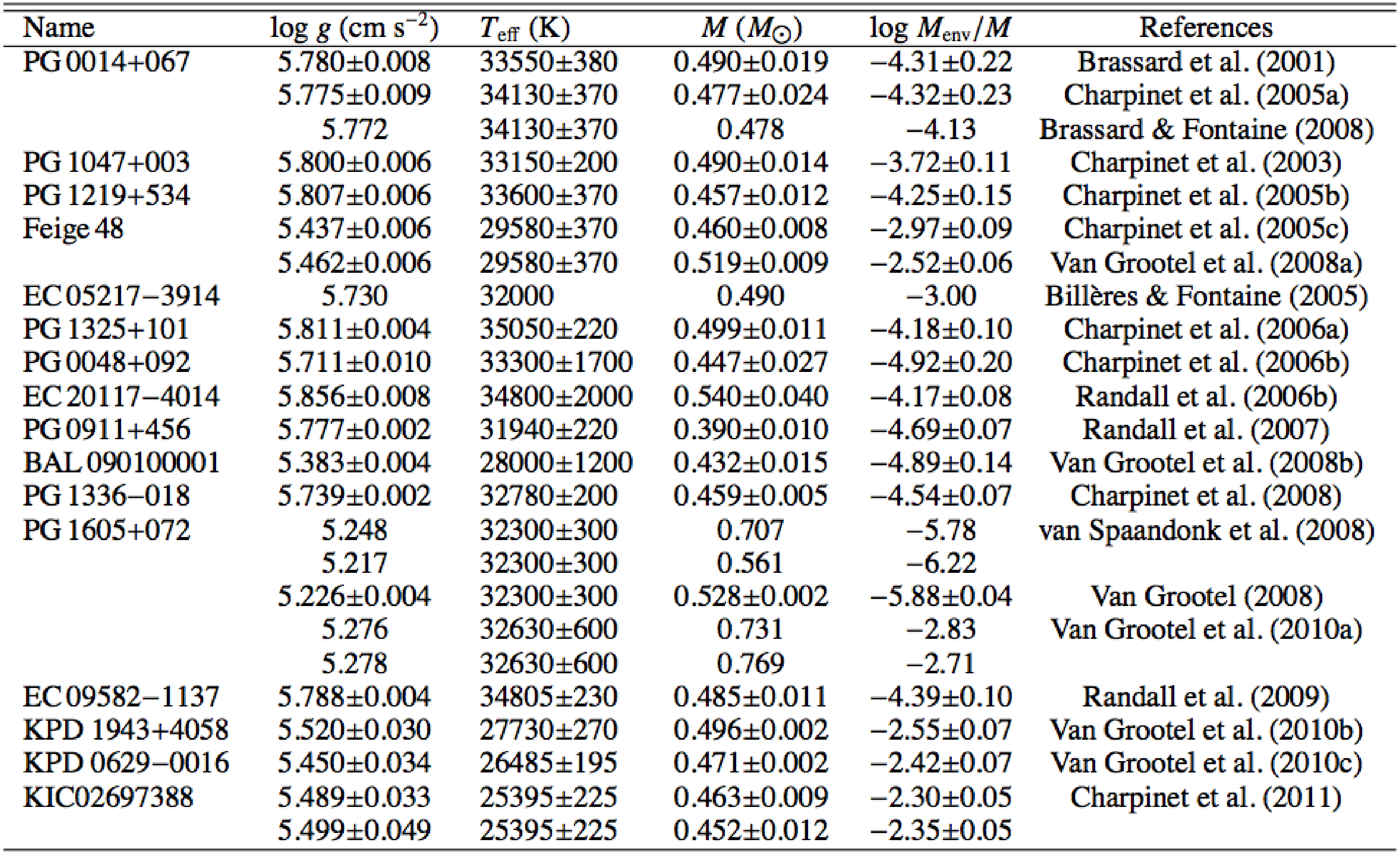
high masses (mergers)

III. The empirical mass distribution of sdB stars

Available samples (of sdBs with known masses)

I. The asteroseismic sample

15 sdB stars modeled by asteroseismology

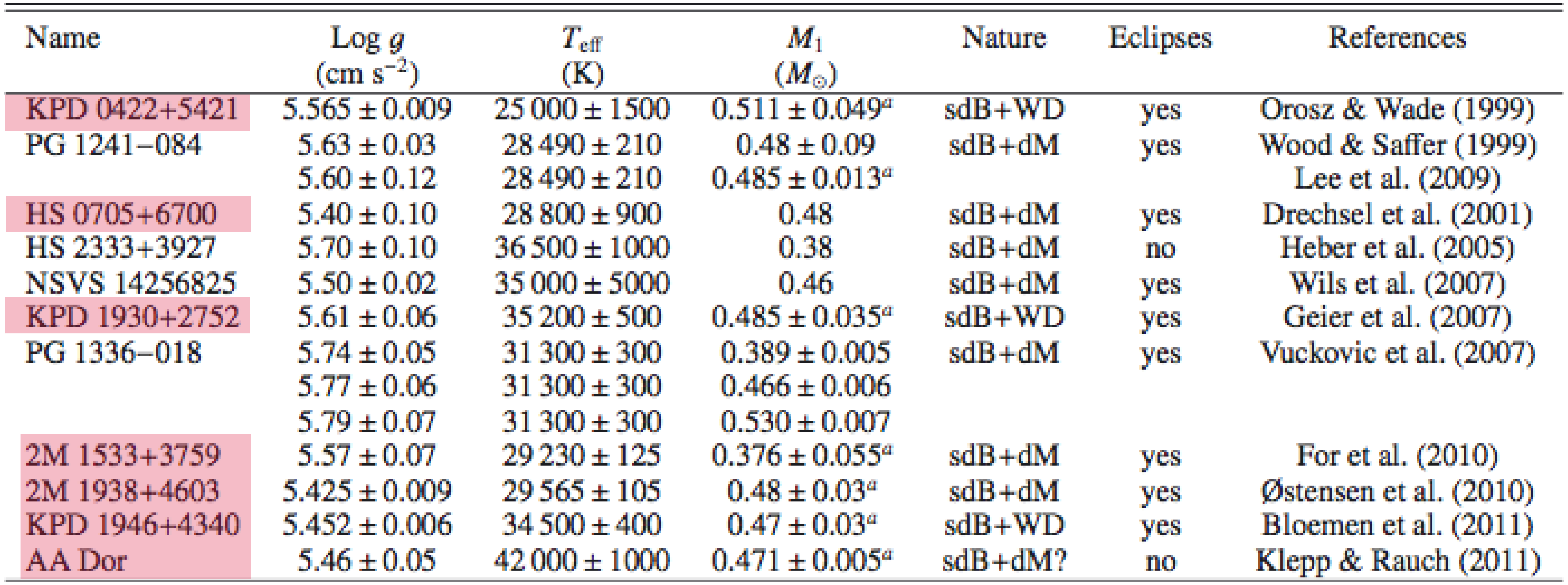


Name	$\log g$ (cm s^{-2})	T_{eff} (K)	M ($M_{\odot}$)	$\log M_{\mathrm{env}}/M$	References
PG 0014+067	5.780±0.008	33550±380	0.490±0.019	−4.31±0.22	Brassard et al. (2001)
	5.775±0.009	34130±370	0.477±0.024	−4.32±0.23	Charpinet et al. (2005a)
	5.772	34130±370	0.478	−4.13	Brassard & Fontaine (2008)
PG 1047+003	5.800±0.006	33150±200	0.490±0.014	−3.72±0.11	Charpinet et al. (2003)
PG 1219+534	5.807±0.006	33600±370	0.457±0.012	−4.25±0.15	Charpinet et al. (2005b)
Feige 48	5.437±0.006	29580±370	0.460±0.008	−2.97±0.09	Charpinet et al. (2005c)
	5.462±0.006	29580±370	0.519±0.009	−2.52±0.06	Van Grootel et al. (2008a)
EC 05217−3914	5.730	32000	0.490	−3.00	Billères & Fontaine (2005)
PG 1325+101	5.811±0.004	35050±220	0.499±0.011	−4.18±0.10	Charpinet et al. (2006a)
PG 0048+092	5.711±0.010	33300±1700	0.447±0.027	−4.92±0.20	Charpinet et al. (2006b)
EC 20117−4014	5.856±0.008	34800±2000	0.540±0.040	−4.17±0.08	Randall et al. (2006b)
PG 0911+456	5.777±0.002	31940±220	0.390±0.010	−4.69±0.07	Randall et al. (2007)
BAL 090100001	5.383±0.004	28000±1200	0.432±0.015	−4.89±0.14	Van Grootel et al. (2008b)
PG 1336−018	5.739±0.002	32780±200	0.459±0.005	−4.54±0.07	Charpinet et al. (2008)
PG 1605+072	5.248	32300±300	0.707	−5.78	van Spaandonk et al. (2008)
	5.217	32300±300	0.561	−6.22	
	5.226±0.004	32300±300	0.528±0.002	−5.88±0.04	Van Grootel (2008)
	5.276	32630±600	0.731	−2.83	Van Grootel et al. (2010a)
	5.278	32630±600	0.769	−2.71	
EC 09582−1137	5.788±0.004	34805±230	0.485±0.011	−4.39±0.10	Randall et al. (2009)
KPD 1943+4058	5.520±0.030	27730±270	0.496±0.002	−2.55±0.07	Van Grootel et al. (2010b)
KPD 0629−0016	5.450±0.034	26485±195	0.471±0.002	−2.42±0.07	Van Grootel et al. (2010c)
KIC02697388	5.489±0.033	25395±225	0.463±0.009	−2.30±0.05	Charpinet et al. (2011)
	5.499±0.049	25395±225	0.452±0.012	−2.35±0.05	

Available samples

II. The binary sample (sdB + WD or dM star)

Light curve modeling + spectroscopy ⇒ mass of the sdB component



Name	Log g (cm s^{-2})	$T_{\rm eff}$ (K)	M_1 ($M_\odot$)	Nature	Eclipses	References
KPD 0422+5421	5.565 ± 0.009	25 000 ± 1500	0.511 ± 0.049^a	sdB+WD	yes	Orosz & Wade (1999)
PG 1241−084	5.63 ± 0.03	28 490 ± 210	0.48 ± 0.09	sdB+dM	yes	Wood & Saffer (1999)
	5.60 ± 0.12	28 490 ± 210	0.485 ± 0.013^a			Lee et al. (2009)
HS 0705+6700	5.40 ± 0.10	28 800 ± 900	0.48	sdB+dM	yes	Drechsel et al. (2001)
HS 2333+3927	5.70 ± 0.10	36 500 ± 1000	0.38	sdB+dM	no	Heber et al. (2005)
NSVS 14256825	5.50 ± 0.02	35 000 ± 5000	0.46	sdB+dM	yes	Wils et al. (2007)
KPD 1930+2752	5.61 ± 0.06	35 200 ± 500	0.485 ± 0.035^a	sdB+WD	yes	Geier et al. (2007)
PG 1336−018	5.74 ± 0.05	31 300 ± 300	0.389 ± 0.005	sdB+dM	yes	Vuckovic et al. (2007)
	5.77 ± 0.06	31 300 ± 300	0.466 ± 0.006			
	5.79 ± 0.07	31 300 ± 300	0.530 ± 0.007			
2M 1533+3759	5.57 ± 0.07	29 230 ± 125	0.376 ± 0.055^a	sdB+dM	yes	For et al. (2010)
2M 1938+4603	5.425 ± 0.009	29 565 ± 105	0.48 ± 0.03^a	sdB+dM	yes	Østensen et al. (2010)
KPD 1946+4340	5.452 ± 0.006	34 500 ± 400	0.47 ± 0.03^a	sdB+WD	yes	Bloemen et al. (2011)
AA Dor	5.46 ± 0.05	42 000 ± 1000	0.471 ± 0.005^a	sdB+dM?	no	Klepp & Rauch (2011)

Need uncertainties to build a mass distribution

⇒ 7 sdB stars retained in this subsample

Extended sample: 15+7 = 22 sdB stars with accurate mass estimates

- 11 (apparently) single stars
- 11 in binaries (including 4 pulsators)

Empirical mass distributions of sdB stars

in the form of an histogram (bin width = σ = 0.024 Ms)

Extended sample:

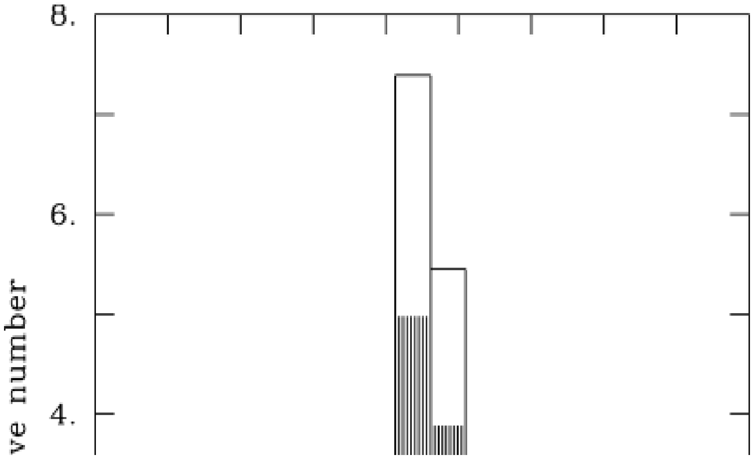
(white)

Mean mass: 0.470 Ms

Median mass: 0.471 Ms

Range of 68.3% of stars:

0.439-0.501 Ms



Asteroseismic sample:

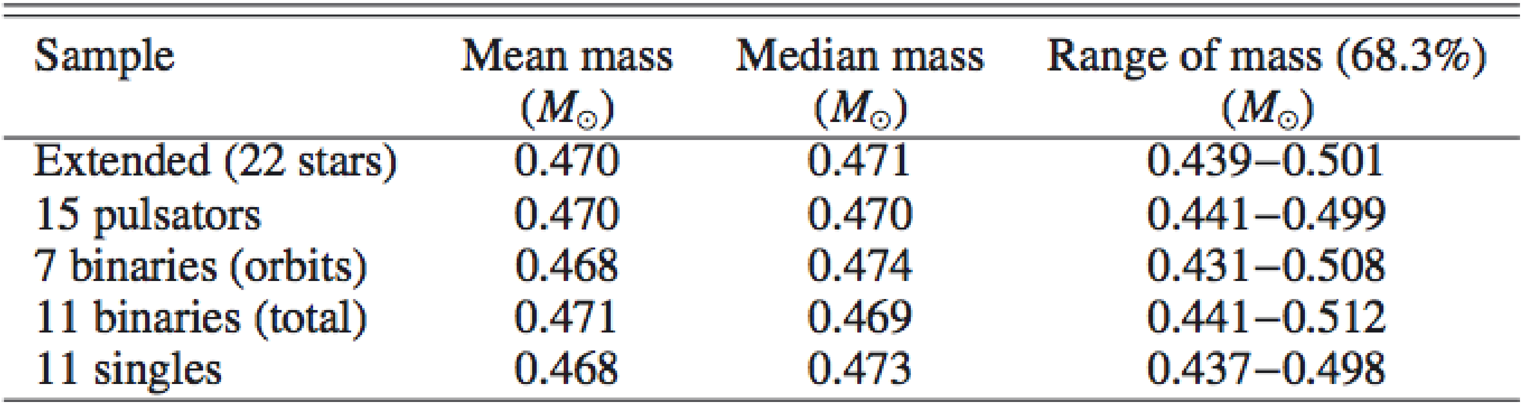
(shaded)

Mean mass: 0.470 Ms

Median mass: 0.470 Ms

Range of 68.3% of stars:

0.441-0.499 Ms



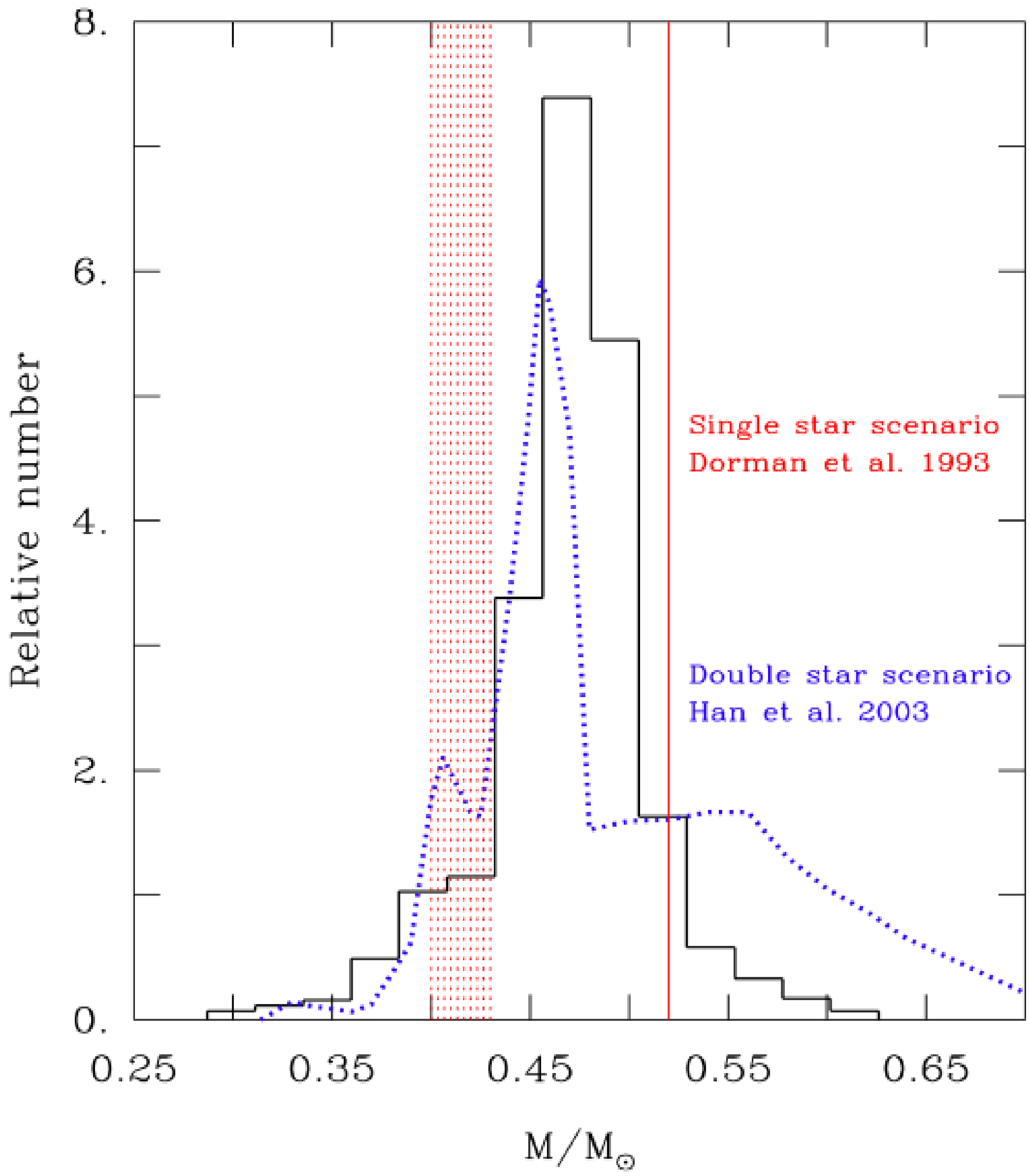
Sample	Mean mass ($M_\odot$)	Median mass ($M_\odot$)	Range of mass (68.3%) ($M_\odot$)
Extended (22 stars)	0.470	0.471	0.439–0.501
15 pulsators	0.470	0.470	0.441–0.499
7 binaries (orbits)	0.468	0.474	0.431–0.508
11 binaries (total)	0.471	0.469	0.441–0.512
11 singles	0.468	0.473	0.437–0.498

No detectable significant differences between distributions

(especially between singles and binaries)

IV. Implications for stellar evolution theory (the formation of sdB stars)

Comparison with theoretical distributions



Single star scenario:

Mass range in

0.40 - 0.43 ≤ M_*/Ms ≤ 0.52

(Dorman et al. 1993)

Double star scenario:

weighted mass distribution

(CE, RLOF, merger)

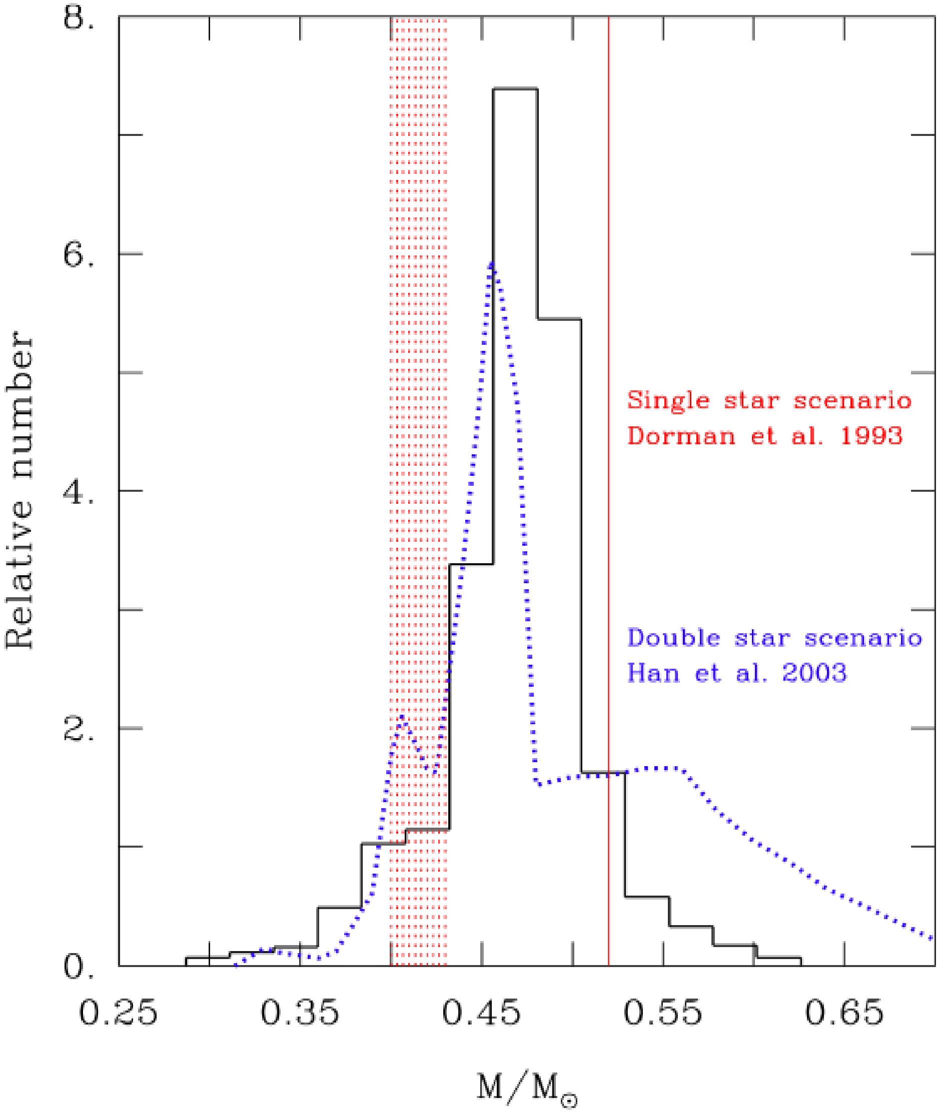
from Han et al. 2003

0.30 ≤ M_*/Ms ≤ 0.70

peak ~ 0.46 Ms (CE, RLOF)

high masses (mergers)

Comparison with theoretical distributions

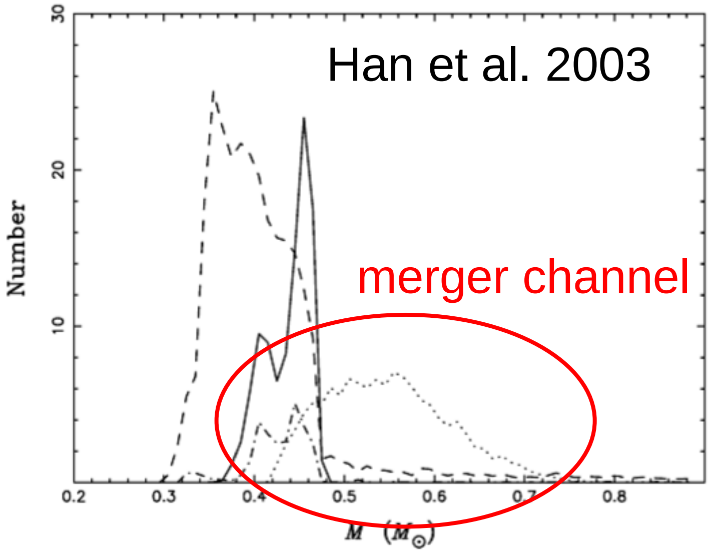


- ✓ A word of caution: still small number statistics (need ~30 stars for a significant sample)
- ✓ Distribution strongly peaked near 0.47 Ms
- ✓ No differences between subsamples (eg, binaries vs single sdB stars)
- ✓ It seems to have a deficit of high mass sdB stars, i.e. from the merger channel. Especially, the single sdBs distribution ≠ merger distribution.

Comparison with theoretical distributions

The single sdBs distribution ≠ merger channel distribution

Sample	Mean mass ($M_\odot$)	Median mass ($M_\odot$)	Range of mass (68.3%; $M_\odot$)
11 singles	0.468	0.473	0.437–0.498



Han et al. 2003

merger channel

Single sdB stars can <u>not</u> be explained only in terms of binary evolution via merger channel

Moreover, Geier & Heber (2012): 105 single or in wide binaries sdB stars:

all are slow rotators (Vsin i < 10 km s-1)

(the majority of) sdB stars **<u>are</u>** post-red giant stars, and post-He flash stars

Extreme mass loss on RGB

If this scenario holds true, the red giant has experienced extreme mass loss on RGB (Red Giant Branch)

What could cause extreme mass loss on RGB?

- **For binary stars:** ok, thanks to the stellar companion
- **For single stars**, it's more difficult:

- Internal rotation => mixing of He => enhanced mass loss on RGB (Sweigart 1997) – "not a simple explanation"
- No differences between single and binaries distributions: it suggests that they form basically in the same way
- Dynamical interactions: Substellar companions (Soker 1998)

Here is the link with the discovery of two close planets orbiting an sdB star!

A consistent scenario

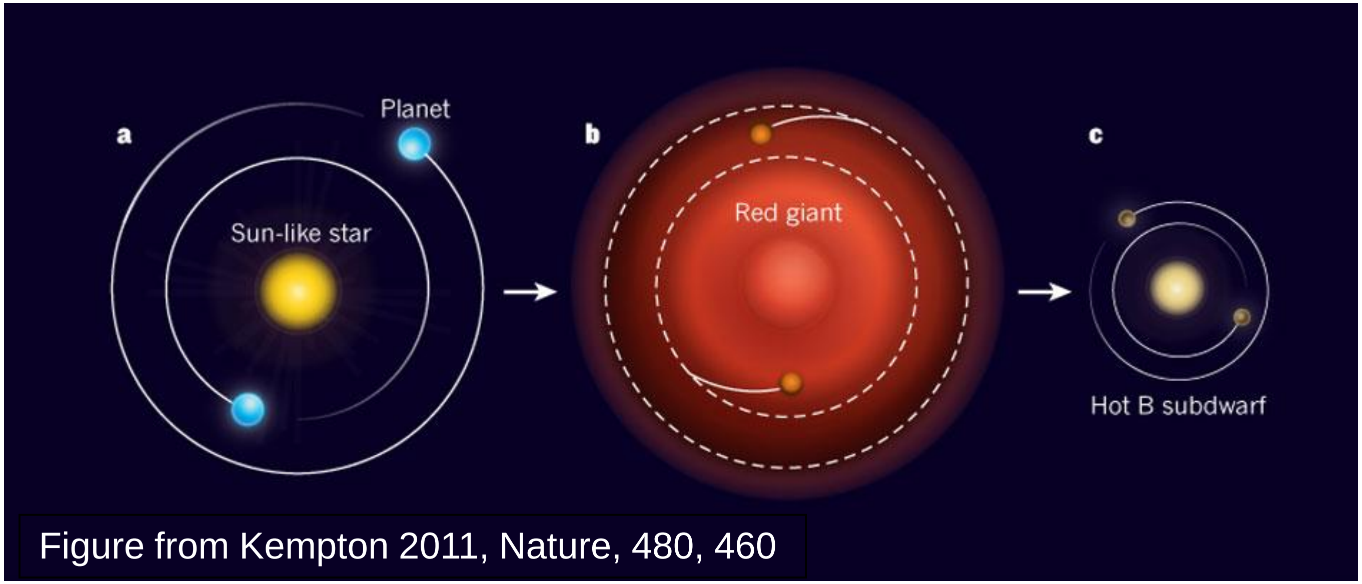


Figure from Kempton 2011, Nature, 480, 460

- ✓ Former close-in giant planets were deeply engulfed in the red giant envelope
- ✓ The planets' volatile layers were removed and only the dense cores survived and migrated where they are now seen
- ✓ The star probably left RGB when envelope was too thin to sustain H-burning shell and experienced a delayed He-flash (or, less likely, He-flash at tip of RGB)
- ✓ Planets are responsible of strong mass loss and kinetic energy loss of the star along the Red Giant Branch
- ✓ As a bonus: this scenario explains why "single" sdB stars are all slow rotators

V. Conclusions and Prospects

Conclusions

✓ No significant differences between distributions of various samples (asteroseismic, light curve modeling, single, binaries, etc.)

✓ **A consistent scenario to form single sdB stars: delayed He-flasher + strong mass loss in the red giant phase due to planets?**

✓~ 7 % of MS stars have closein giant planets that will be engulfed during the red giant phase

→ such formation from **star/planet(s) interaction(s)** may be fairly common

Outlook:

✓ Currently only 22 objects: 11 single stars and 11 in binaries

✓~100 pulsators are now known (e.g. thanks to *Kepler*)

✓ Both light curve modeling and asteroseismology are a challenge (accurate spectroscopic and photometric observations, stellar models, etc.)