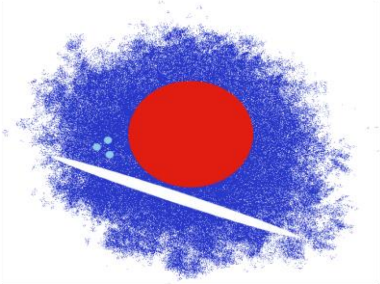
Ageing low-mass stars: from red giants to white dwarfs

40th Liege International Astrophysical Colloquium



The mass distribution of sdB stars from asteroseismology and other means: Implications for stellar evolution theory

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I. Introduction to 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)

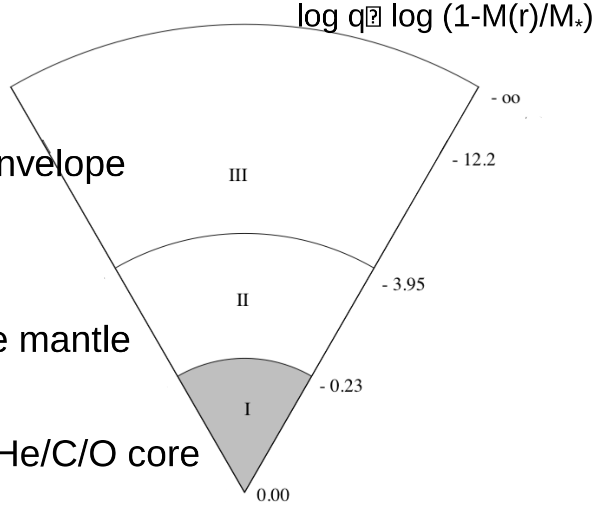
- convective He-burning core (I), radiative He mantle (II) and very thin H-rich envelope (III)
- lifetime of ~ 10^8 yr (100 Myr) on EHB, then evolve directly as low-mass white dwarfs
- ~50% of sdB stars reside in binary systems, generally in close orbit ($P_{\mathrm{orb}} \leq$ 10 days)

Two classes of multi-periodic sdB pulsators:

> 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 !

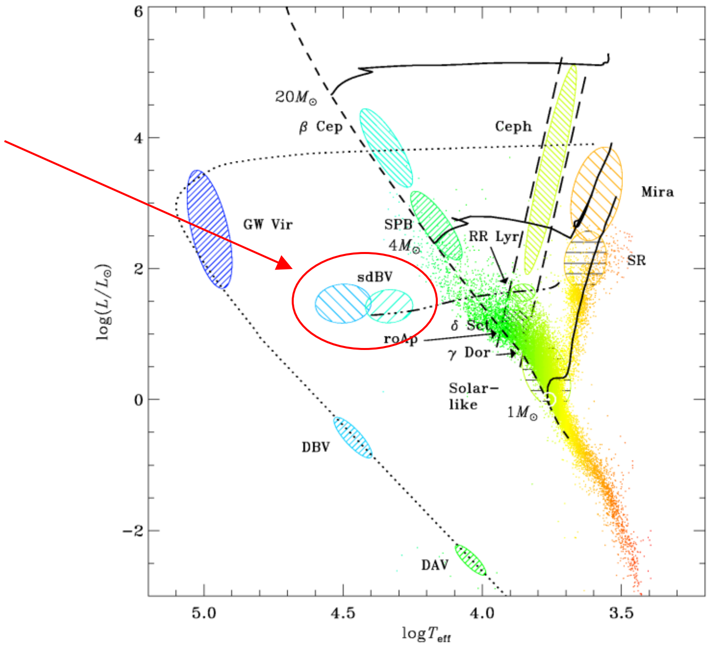
$\log q \equiv \log(1-M(r)/M_*)$



H-rich envelope

He mantle

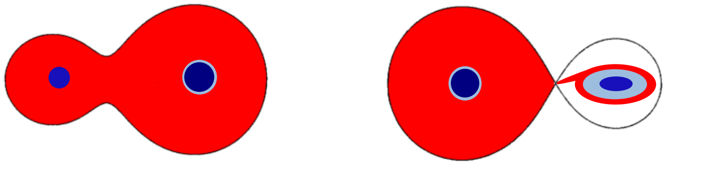
He/C/O core



The formation of sdB stars

How such stars form has been 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 close stellar companion

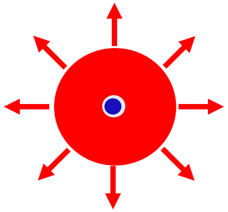
- **For single sdB stars (~50%)**

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)



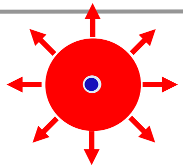
2. The merger scenario:

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

The formation of sdB stars

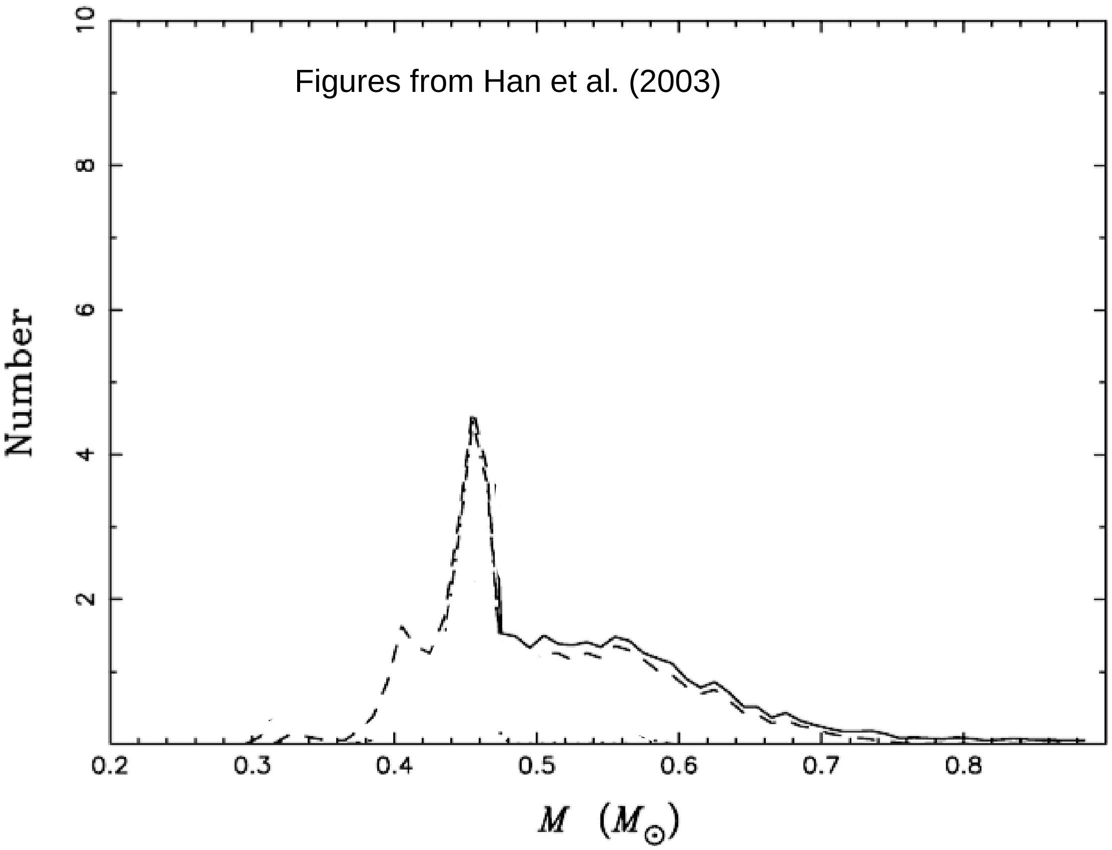
- Single star evolution: Mass range in $0.40 - 0.43 \le M_*/M_s \le 0.52$

  (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)

$0.30 \le M_*/M_s \le 0.70$

peak ~ 0.46 Ms (CE, RLOF)

high masses (mergers)

Method for sdB asteroseismology

Search the star model(s) whose theoretical periods best fit all the observed ones, in order to minimize

$$S^2 = \sum \frac{1}{\sigma}(P_{\mathrm{obs}} - P_{\mathrm{th}})^2$$

- Static models including detailed envelope microscopic diffusion (nonuniform envelope Fe abundance)
- Efficient optimization codes (based on *Genetic Algorithms*) are used to find the minima of S^2, i.e. the potential asteroseismic solutions

> Example: PG 1336-018, pulsating sdB + dM eclipsing binary

✓ Light curve modeling (Vuckovic et al. 2007):

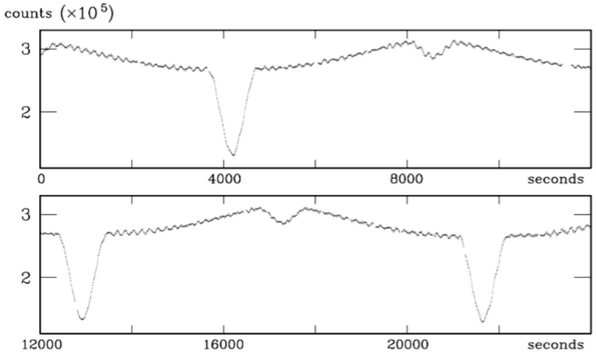
I. $M_{tot} = 0.389 \pm 0.005\ M_s$ et $R = 0.14 \pm 0.01\ R_s$

II. $M_{tot} = 0.466 \pm 0.006\ M_s$ et $R = 0.15 \pm 0.01\ R_s$

III. $M_{tot} = 0.530 \pm 0.007\ M_s$ et $R = 0.15 \pm 0.01\ R_s$

✓ Seismic analysis (Charpinet et al. 2008):

$M_{tot} = 0.459 \pm 0.005\ M_s$ et $R = 0.151 \pm 0.001\ R_s$

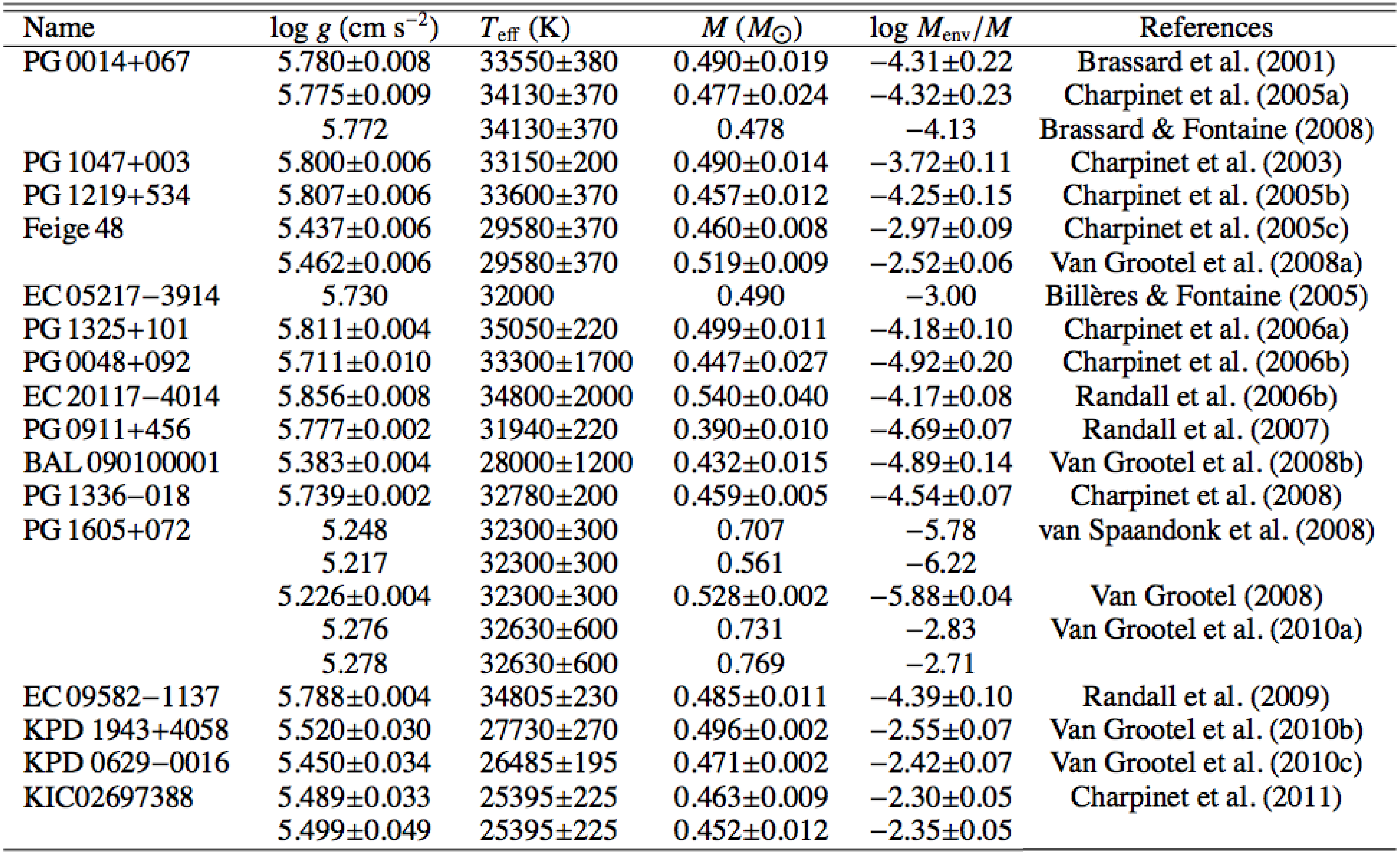


⇒ Our asteroseismic method is sound and free of significant systematic effects

II. The empirical mass distribution of sdB stars (from asteroseismology and light curve modeling)

Available samples (of sdBs with known masses)

I. The asteroseismic sample



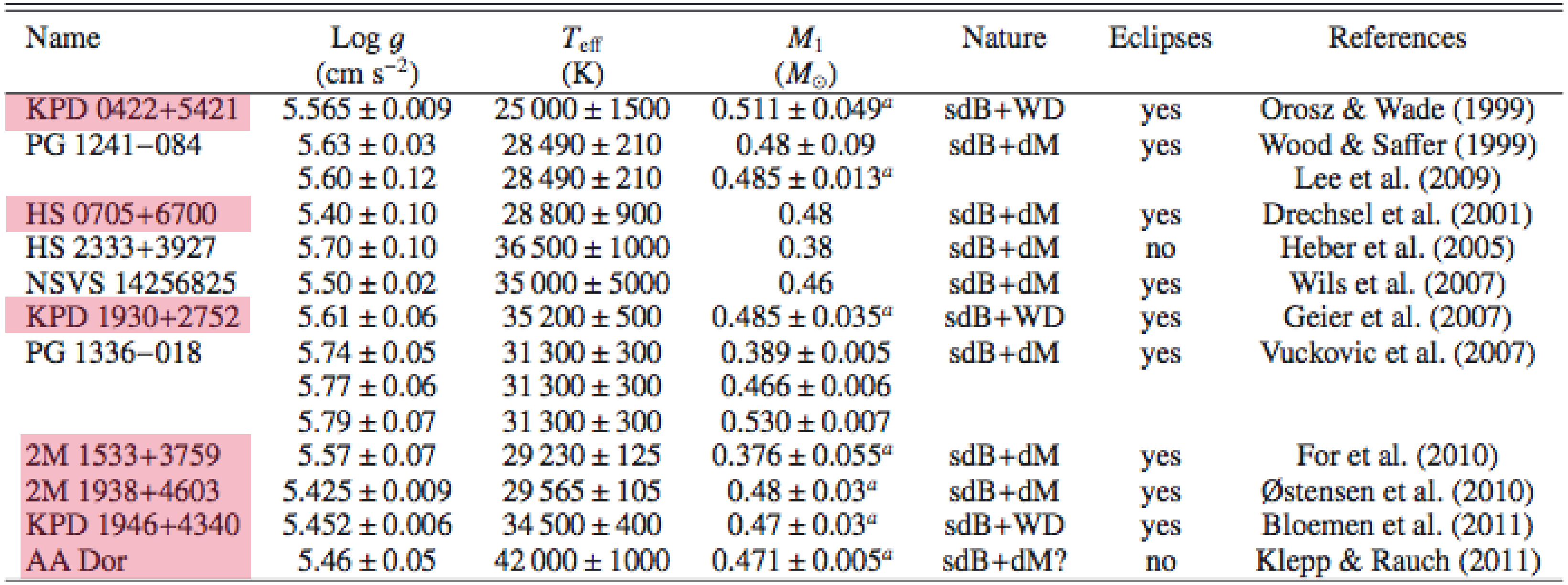
Name	$\log g$ (cm s^{-2})	$T_{\rm eff}$ (K)	M ($M_\odot$)	$\log M_{\rm env}/M$	References
PG 0014+067	5.780±0.008	33550±380	0.490±0.019	−4.31±0.22	Brassard et al. (2001)
	5.775±0.009	34130±370	0.477±0.024	−4.32±0.23	Charpinet et al. (2005a)
	5.772	34130±370	0.478	−4.13	Brassard & Fontaine (2008)
PG 1047+003	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	

15 sdB stars modeled by asteroseismology

(we took the most recent value in case of several analyses)

Available samples

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



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

Light curve modeling + spectroscopy ⇒ mass of the sdB component

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)

Building the mass distributions (Fontaine et al. 2012)

I. Assumption of a normal distribution

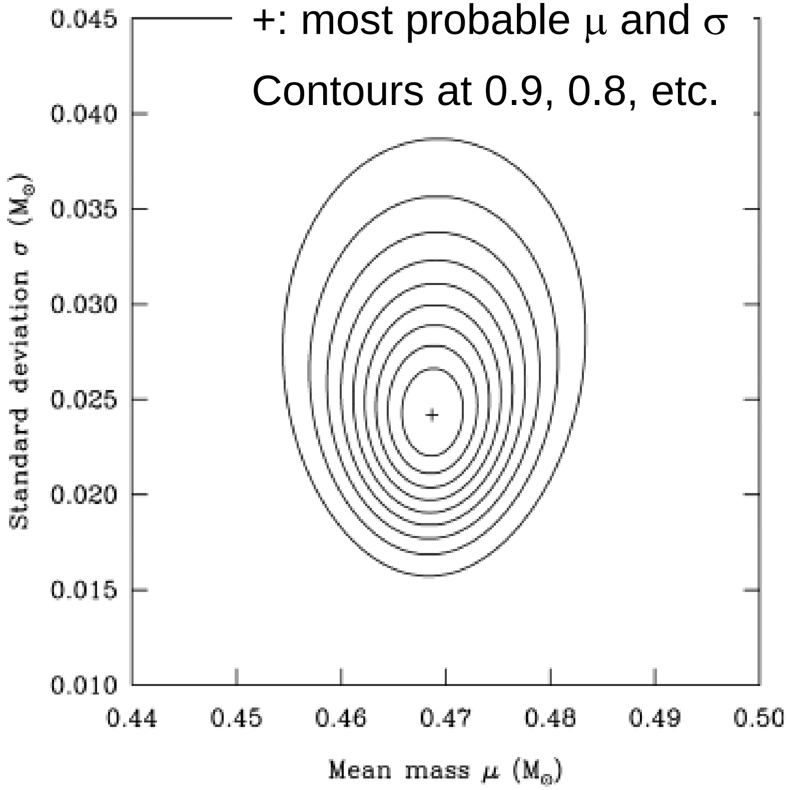
$$L(\mu, \sigma) = \prod_{i=1}^{N} [2\pi(\sigma^2 + \sigma_i^2)]^{-1/2} \exp\{-\frac{(m_i - \mu)^2}{2(\sigma^2 + \sigma_i^2)}\}$$

μ: mean mass

σ: standard deviation

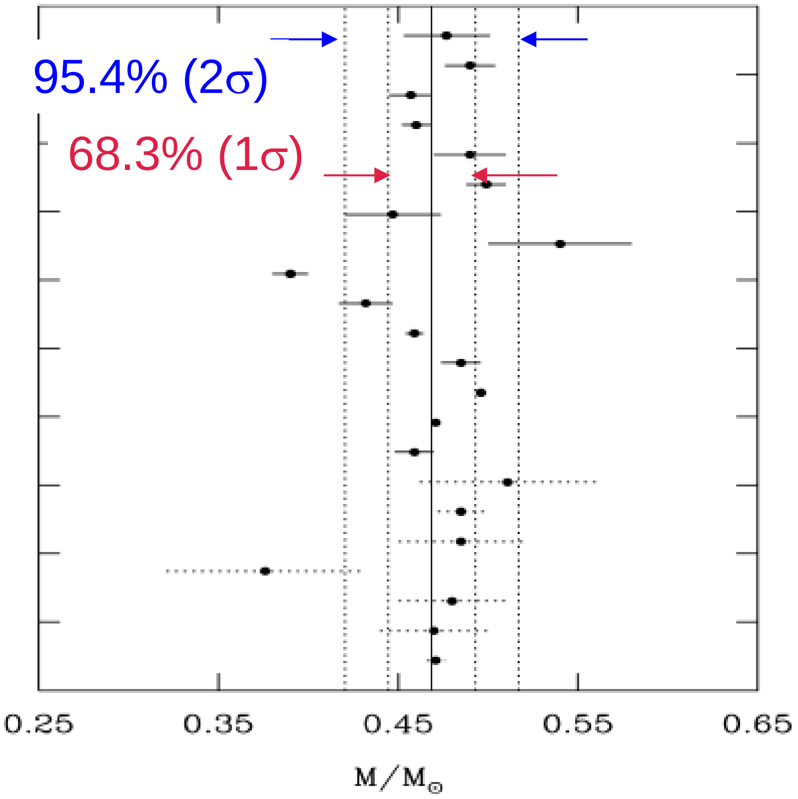
Extended sample (N=22): $\mu = 0.469$ Ms and $\sigma = 0.024$ Ms

Asteroseismic sample (N=15): $\mu = 0.467$ Ms and $\sigma = 0.027$ Ms



+: most probable μ and σ

Contours at 0.9, 0.8, etc.



95.4% (2σ)

68.3% (1σ)

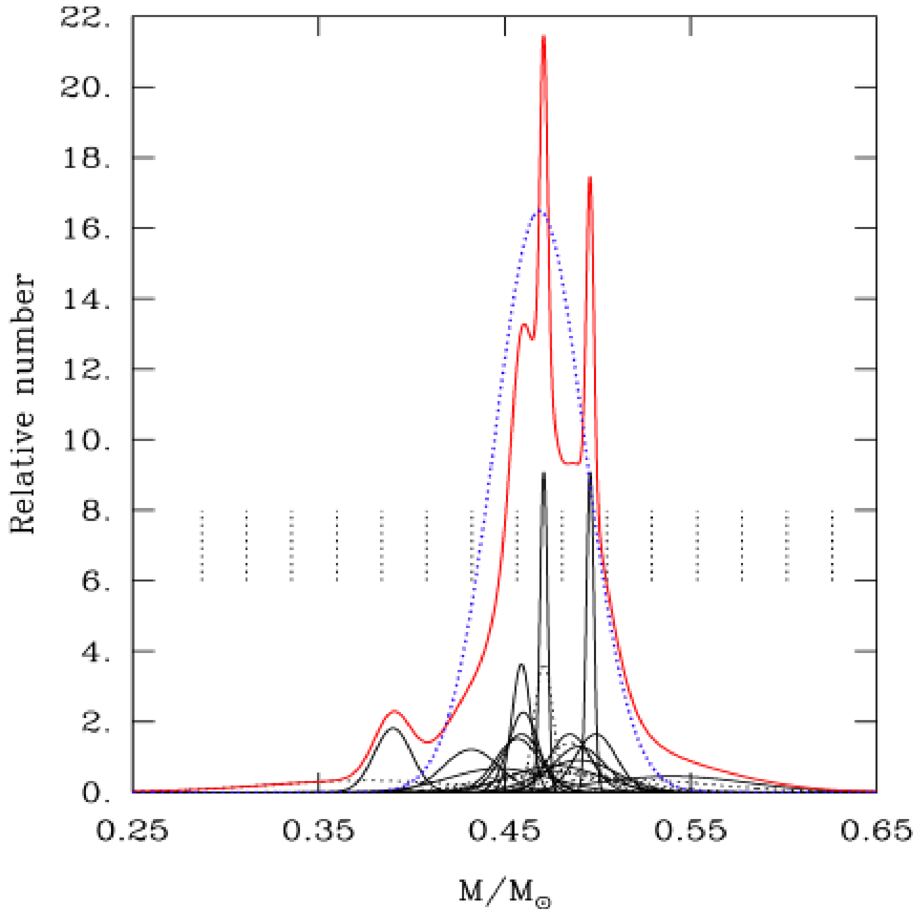
Building the mass distribution

II. Model-free distribution

(only σ_i's are assumed to obey normal distribution law)

Red curve: addition of all sdBs (mass with uncertainties) in extended sample

Blue curve: normal distribution ($\mu = 0.469$ Ms and $\sigma = 0.024$ Ms)



Building the mass distributions

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

Extended sample:

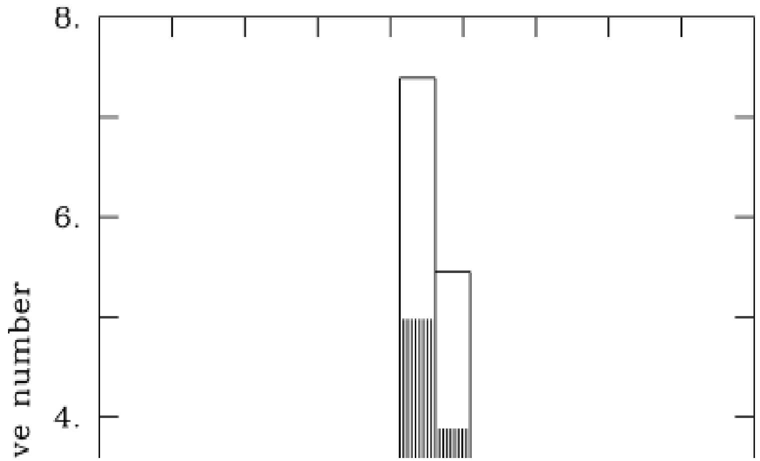
(white)

Mean mass: 0.470 Ms

Median mass: 0.471 Ms

Range of 68.3% of stars:

0.439-0.501 Ms



Asteroseismic sample:

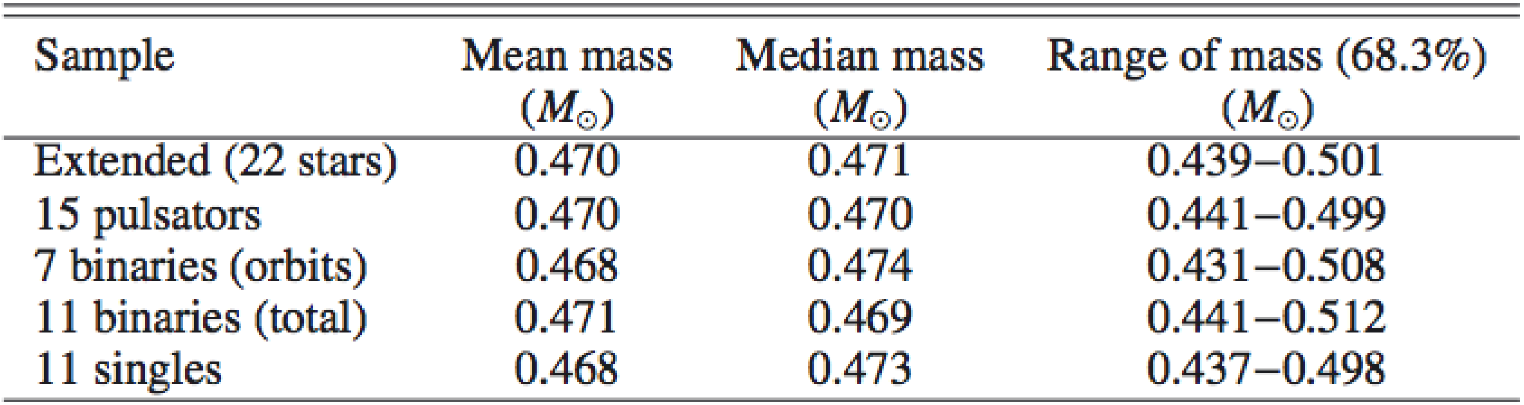
(shaded)

Mean mass: 0.470 Ms

Median mass: 0.470 Ms

Range of 68.3% of stars:

0.441-0.499 Ms



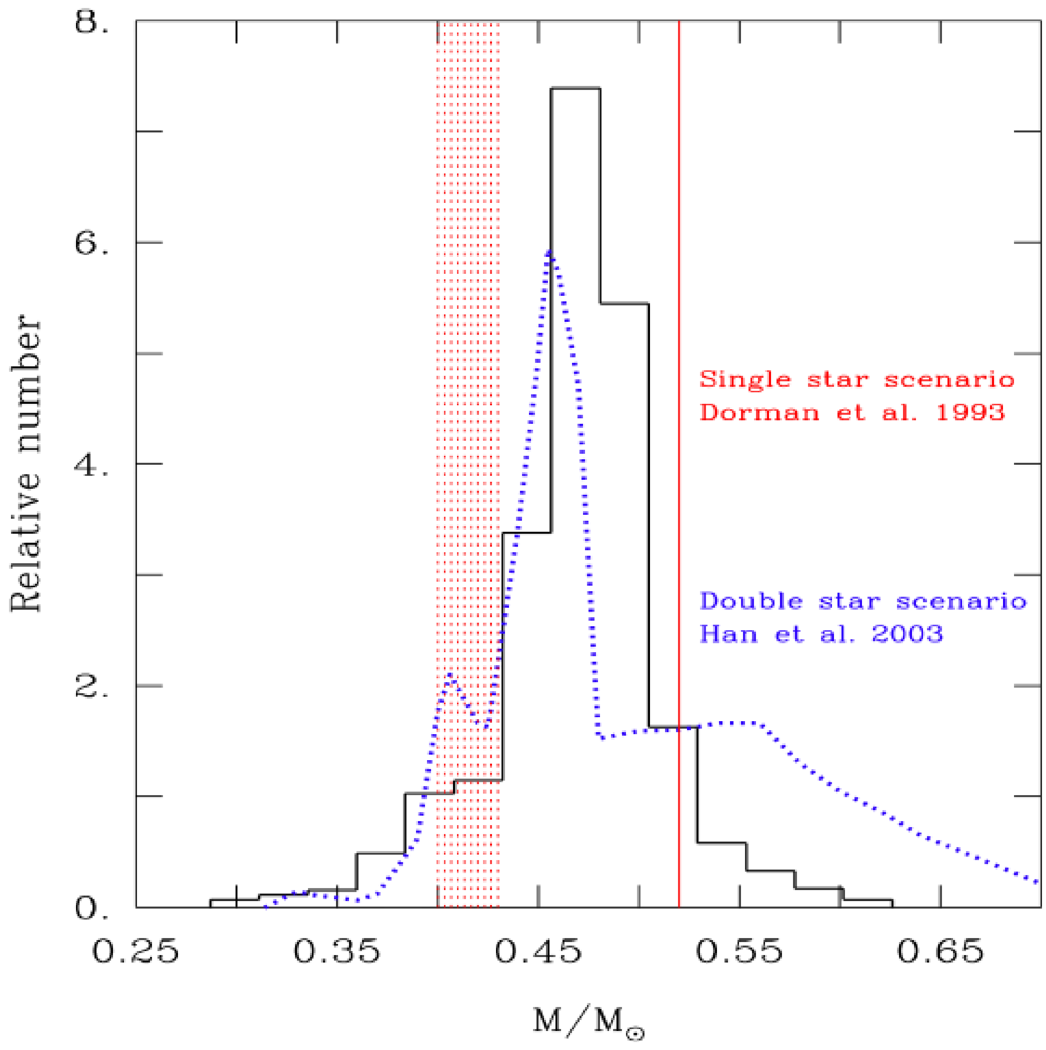
Sample	Mean mass ($M_\odot$)	Median mass ($M_\odot$)	Range of mass (68.3%) ($M_\odot$)
Extended (22 stars)	0.470	0.471	0.439–0.501
15 pulsators	0.470	0.470	0.441–0.499
7 binaries (orbits)	0.468	0.474	0.431–0.508
11 binaries (total)	0.471	0.469	0.441–0.512
11 singles	0.468	0.473	0.437–0.498

No detectable significant differences between distributions

(especially between singles and binaries)

III. 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

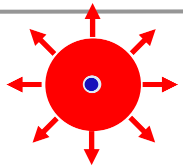
0.30 ≤ M_*/Ms ≤ 0.70

peak ~ 0.46 Ms (CE, RLOF)

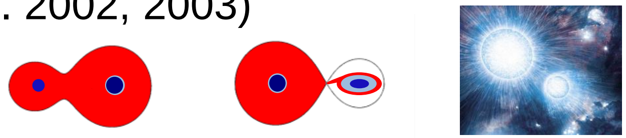
high masses (mergers)

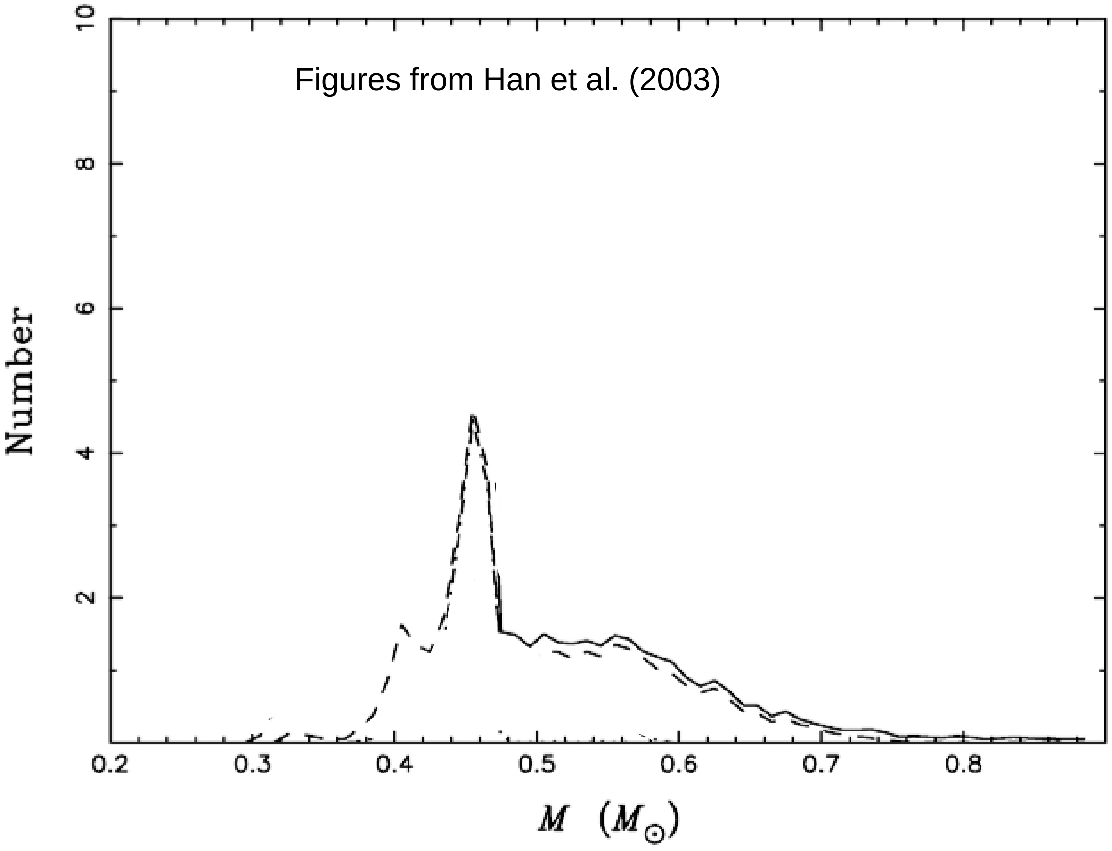
The formation of sdB stars

- Single star evolution: Mass range in $0.40 - 0.43 \leq M_*/Ms \leq 0.52$
  (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:

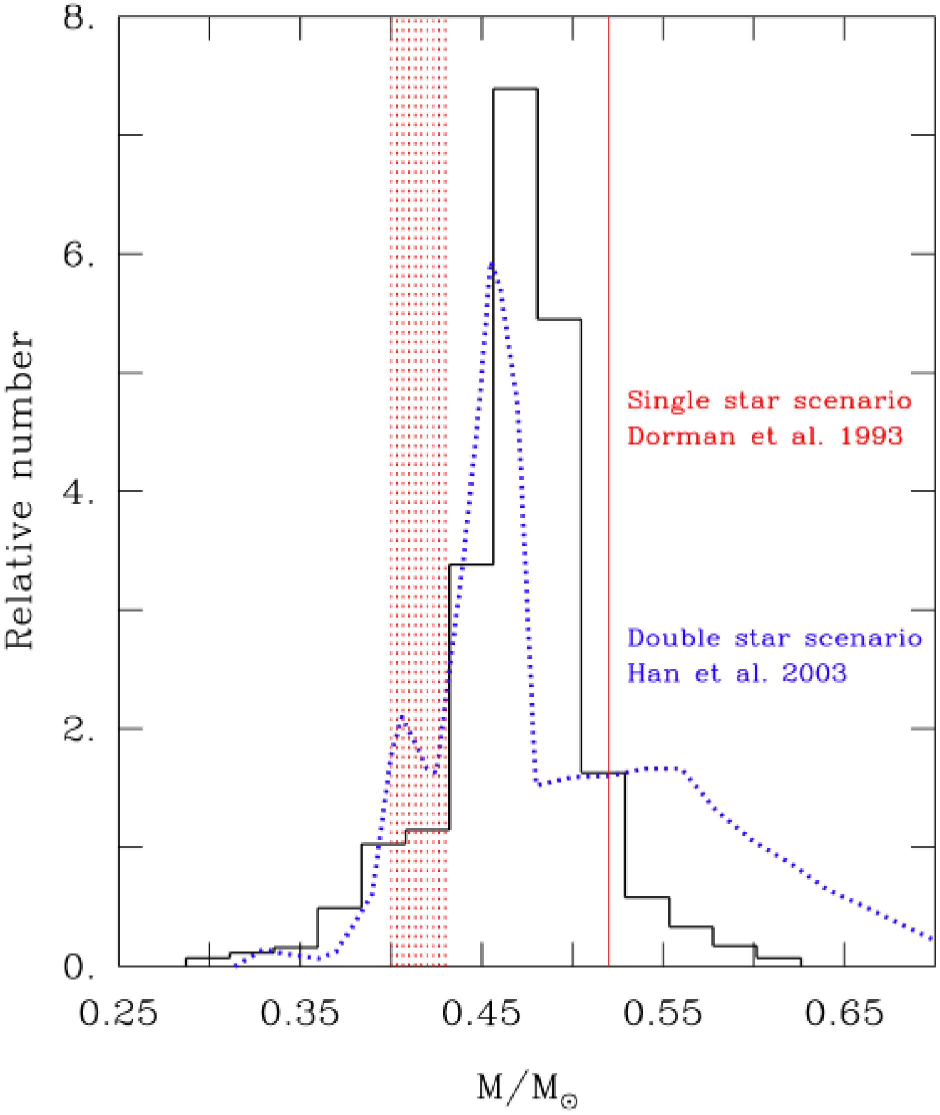
(including selection effects)

$0.30 \leq M_*/Ms \leq 0.70$

peak ~ 0.46 Ms (CE, RLOF)

high masses (mergers)

Comparison with theoretical distributions

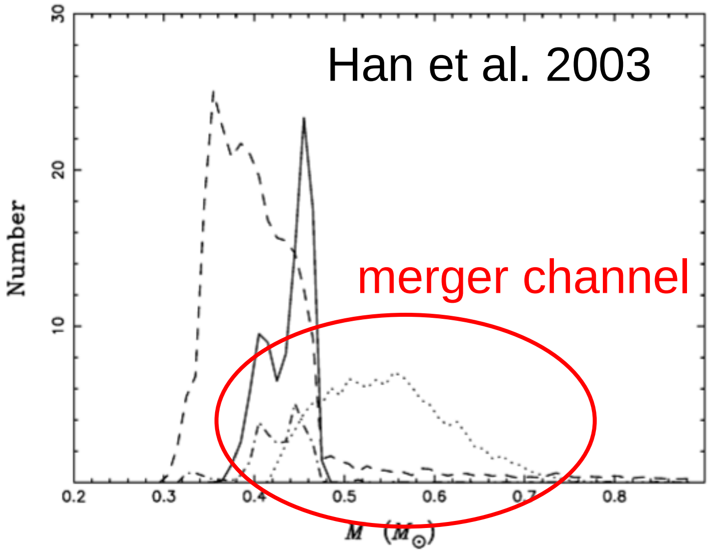


- ✓ A word of caution: still small number statistics (need ~30 stars for a significant sample)
- ✓ Distribution strongly peaked near 0.47 Ms
- ✓ No differences between subsamples (eg, binaries vs single sdB stars)
- ✓ It seems to have a deficit of high mass sdB stars, i.e. from the merger channel. Especially, 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 not 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 **are** post-RGB stars

(the majority of) sdB stars **are** post-RGB stars, and even post He-flash stars

What does it imply ?

The star has removed all but a small fraction of its envelope
and has reached the minimum mass to trigger He-flash

- at tip of RGB, as a classic RGB-tip flasher ? (classic way for HB stars)

-> It's rather unlikely that the 2 events occur at the same time !

- an alternative (old and somewhat forgotten) idea:

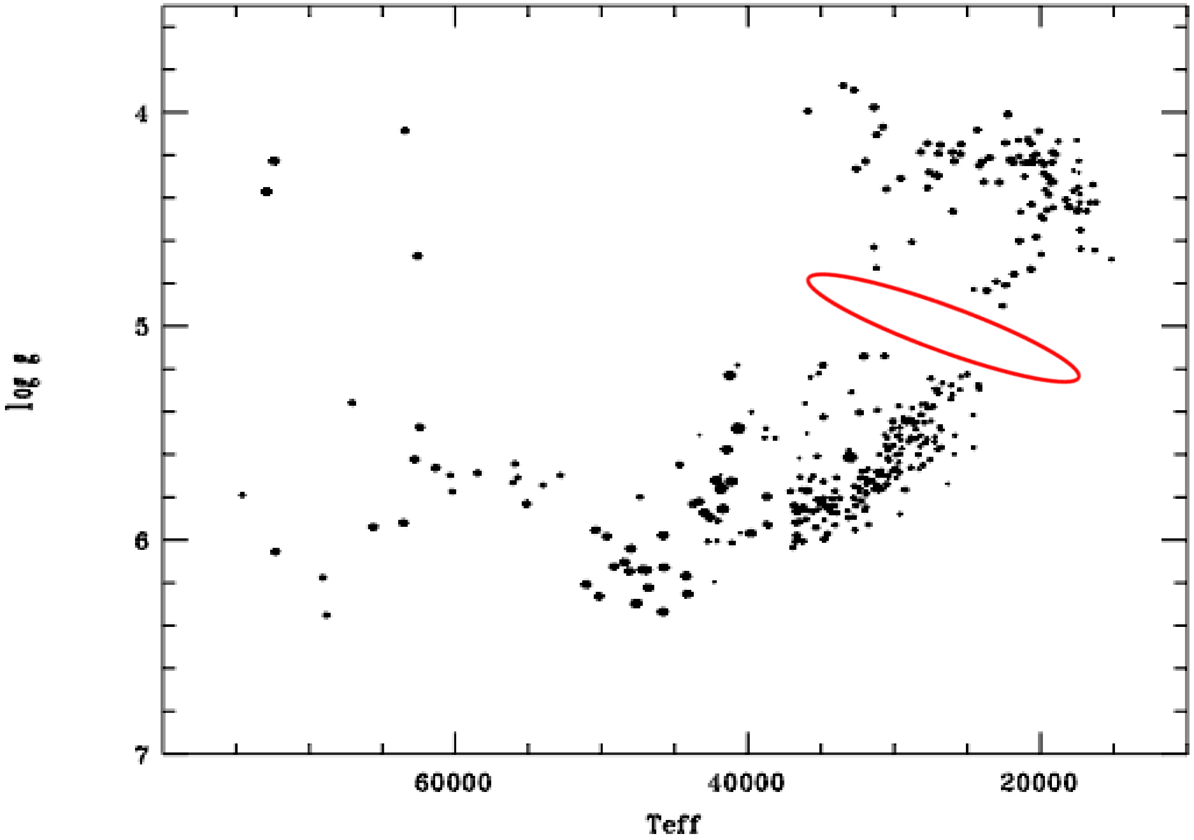
Hot He-flashers (Castellani&Castellani 1993; D'Cruz et al. 1996)

i.e., stars that experience a delayed He-flash during contraction, at higher T_{eff}, after leaving the RGB before tip
(H-burning shell stops due to strong mass loss on RGB)

D'Cruz et al. (1996) showed that such stars populate the EHB, with similar (core) masses

Another hint: Horizontal branch/EHB morphology

There is a gap between EHB and classic blue HB (BHB)



Green et al. (2008)

Size of dots related to He abundance

This suggests something “different” for the formation of EHB and HB stars

Extreme mass loss on RGB

If delayed-flash scenario holds true, the star has experienced strong mass loss on RGB (which stopped H-burning shell and forced the star to collapse)

What could cause extreme mass loss on RGB ?

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

- Internal rotation => mixing of He => enhanced mass loss on RGB (Sweigart 1997)

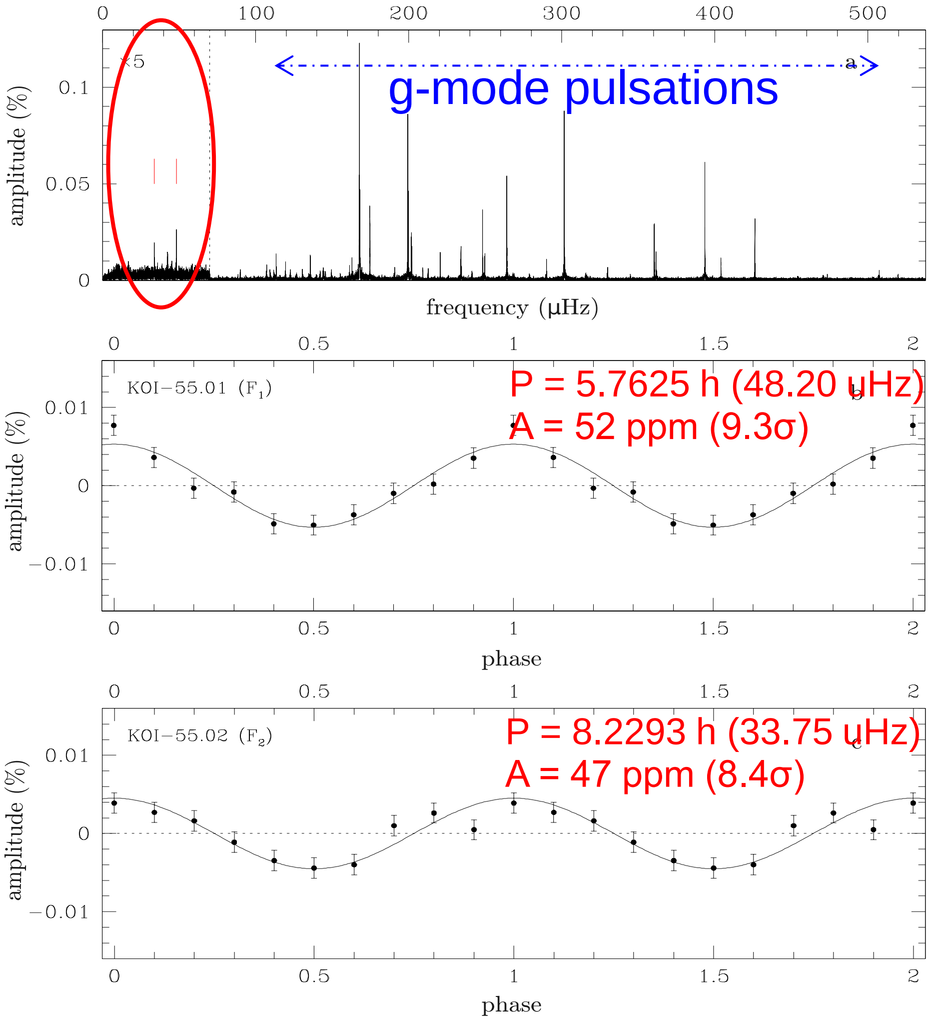
- Dynamical interactions: Substellar companions (Soker 1998)

Indeed, Charpinet et al. discovered two close planets orbiting an sdB star (Nature, 480, 496)

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.

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 ~ 39.23 d)
- ✓ Contamination from a fainter nearby star? → rejected based on pixel data analysis
- ✓ Modulations of orbital origin?

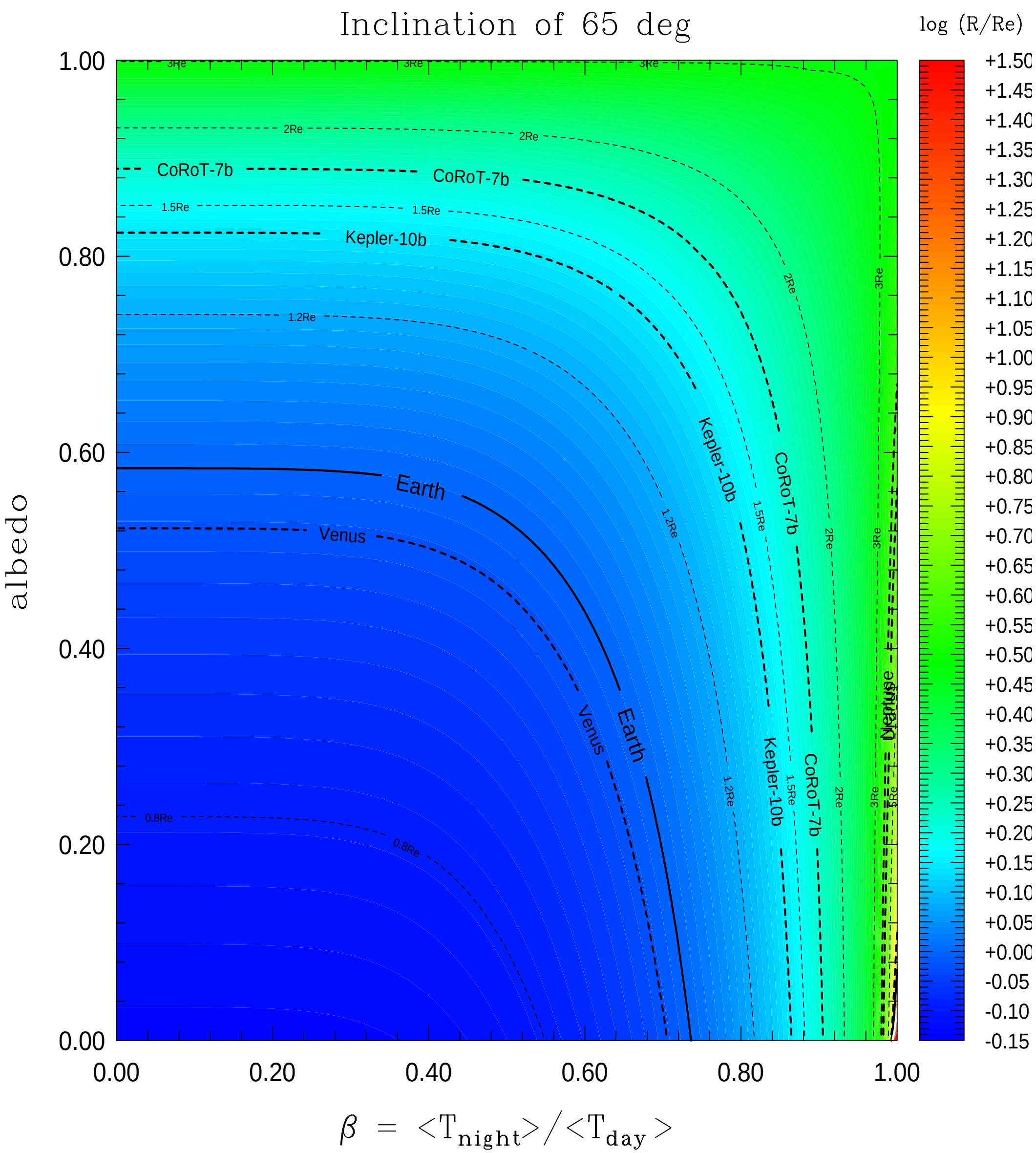
What sizes should these objects have to produce the observed variations?

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

-> The estimated radii are comparable to Earth radius

↓

We have two small planets, orbiting very close (0.006 and 0.008 AU) to their host star

A consistent scenario

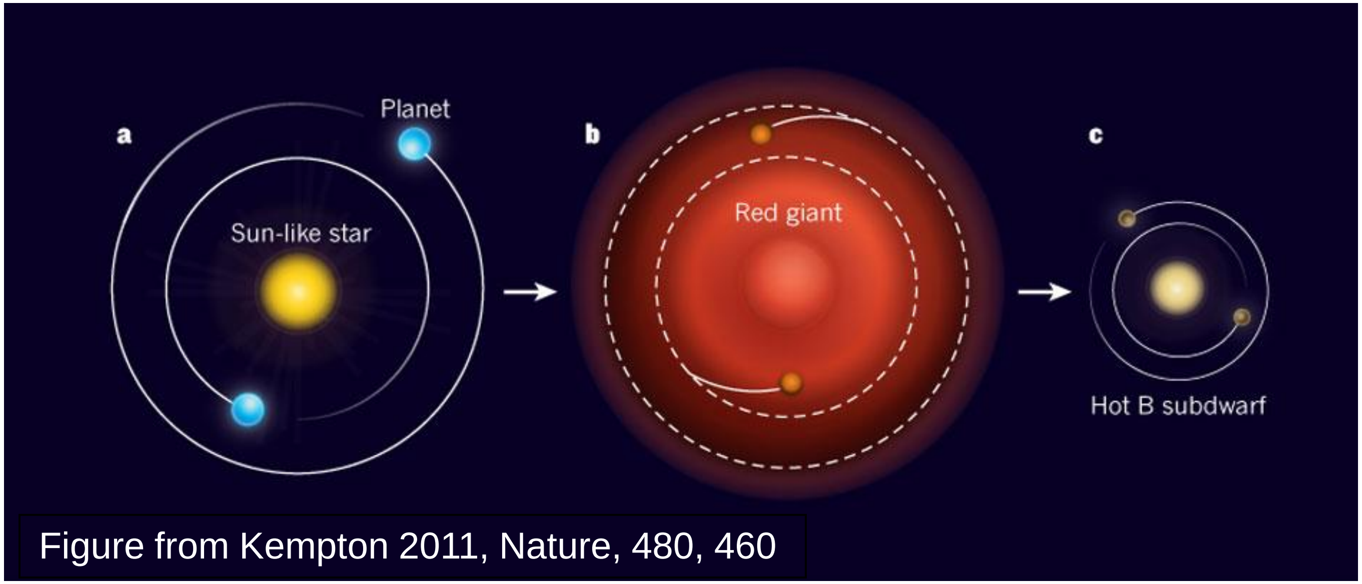


Figure from Kempton 2011, Nature, 480, 460

- ✓ 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 RGB
- ✓ As a bonus: this scenario explains why "single" sdB stars are all slow rotators

IV. Conclusions and Prospects

Conclusions

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

✓ Single star evolution scenario <u>does</u> exist; importance of the merger scenario? (single stars with presumably fast rotation)

✓ **A consistent scenario to form single sdB stars: delayed He-flasher + strong mass loss on RGB 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

But:

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

✓ Among > 2000 known sdB, ~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.)