What asteroseismology can teach us about stellar evolution: the case of subdwarf B stars

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I. What are subdwarf B (sdB) stars?
The subdwarf B (sdB) stars

Hot ($T_{\text{eff}} \sim 30,000$ K) and compact ($\log g \sim 5.5$) stars that are on an intermediate stage of evolution

Internal structure:

I. He $\rightarrow$ C+O fusion (convective core)
II. He mantle
III. very thin H-rich envelope

($M_{\text{env}} \sim 10^{-5} - 2.10^{-2}$ Msun pour $M_* \sim 0.5$ Msun)

Two classes of multi-periodic sdB pulsators: we can use asteroseismology
The formation of sdB stars

How such stars form is a long standing problem of stellar evolution

Main difficulty: the progenitor core has to reach the minimum mass for He-burning ignition, but the star must lose almost all of its envelope!!

1. Single star evolution:
   enhanced and tuned mass loss at tip of red giant branch, at He-burning ignition
   Possible mechanism difficult and unclear

2. The merger scenario:
   Two low mass He white dwarfs merge to form a He core burning sdB star
   favoured

• For sdB in binaries (~50%)
  in the red giant phase: Common envelope ejection (CE), stable mass transfer by Roche lobe overflow (RLOF)

• For single sdB stars (~50%)
  Remains the stripped core of the former red giant, which is the sdB star, with a close stellar companion
The formation of sdB stars

• **Single star evolution** ("almost impossible"): Mass range in $0.40 - 0.43 \leq M/\text{Ms} \leq 0.52$
  (Dorman et al. 1993)

• **Binary star evolution**: numerical simulations on binary population synthesis
  (Han et al. 2002, 2003)

Figures from Han et al. (2003)
The formation of sdB stars

- **Single star evolution** ("almost impossible"): Mass range in $0.40 - 0.43 \leq M_*/M_\odot \leq 0.52$ (Dorman et al. 1993)
- **Binary star evolution**: numerical simulations on binary population synthesis (Han et al. 2002, 2003)

Weighted mean distribution for binary evolution: (including selection effects)

$0.30 \leq M_*/M_\odot \leq 0.70$
peak $\sim 0.46 M_\odot$ (CE, RLOF)
high masses (mergers)
The formation of sdB stars

- **Single star evolution** ("almost impossible"): Mass range in $0.40 - 0.43 \leq M_*/M_\odot \leq 0.52$
  
  (Dorman et al. 1993)

- **Binary star evolution**: numerical simulations on binary population synthesis
  
  (Han et al. 2002, 2003)

This is the theoretical mass distributions we want to test by asteroseismology

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

peak ~ $0.46$ $M_\odot$ (CE, RLOF)

high masses (mergers)
II. Asteroseismology of sdB stars
The method for sdB asteroseismology

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

\[ S^2 = \sum \frac{1}{\sigma} (P_{\text{obs}} - P_{\text{th}})^2 \]

- Optimization codes (based on *Genetic Algorithms*) to find the minima of \( S^2 \)
- External constraints: \( T_{\text{eff}} \), \( \log g \) from spectroscopy
- Results: global parameters (mass, radius), internal structure (envelope & core mass, …)

> Example: PG 1336-018, pulsating sdB + dM eclipsing binary (a unique case!)

- Light curve modeling (Vuckovic et al. 2007):
  \[ M = 0.466 \pm 0.006 \, M_\odot, \, R = 0.15 \pm 0.01 \, R_\odot, \]
  \[ \text{and } \log g = 5.77 \pm 0.06 \]

- Seismic analysis (Van Grootel et al. 2013):
  \[ M = 0.471 \pm 0.006 \, M_\odot, \, R = 0.1474 \pm 0.0009 \, R_\odot, \]
  \[ \text{and } \log g = 5.775 \pm 0.007 \]

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

Figure from Vuckovic et al. (2007)
III. The empirical mass distribution of sdB stars (from asteroseismology and light curve modeling)
### Available samples (of sdBs with known masses)

#### I. The asteroseismic sample

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

15 sdB stars modeled by asteroseismology
Available samples

II. Non-pulsating sdB in binaries

Light curve modeling + spectroscopy \(\Rightarrow\) mass of the sdB component

Need uncertainties to build a mass distribution

\(\Rightarrow\) 7 sdB stars retained in this subsample

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

- 11 single stars (confirmed to have no stellar companion)
- 11 in binaries (including 4 pulsators)
Building the mass distributions

Extended sample: (white, 22 stars)
Mean mass: 0.470 Ms
Median mass: 0.471 Ms
Range of 68.3% of stars: 0.439-0.501 Ms

Asteroseismic sample: (shaded, 15 stars)
Mean mass: 0.470 Ms
Median mass: 0.470 Ms
Range of 68.3% of stars: 0.441-0.499 Ms

Binning the distribution in the form of an histogram (bin width = $\sigma = 0.024$ Ms)
Building the mass distributions

Extended sample: (white, 22 stars)
Mean mass: 0.470 $M_\odot$
Median mass: 0.471 $M_\odot$
Range of 68.3% of stars: 0.439-0.501 $M_\odot$

Asteroseismic sample: (shaded, 15 stars)
Mean mass: 0.470 $M_\odot$
Median mass: 0.470 $M_\odot$
Range of 68.3% of stars: 0.441-0.499 $M_\odot$

No detectable significant differences between distributions (especially between singles and binaries)
IV. Implications for stellar evolution  
(the formation of sdB stars)
Comparison with theoretical distributions

Single star scenario:
Mass range in
$0.40 - 0.43 \leq \frac{M_*}{M_\odot} \leq 0.52$
(Dorman et al. 1993)

Double star scenario:
weighted mass distribution
(CE, RLOF, merger)
from Han et al. 2003
$0.30 \leq \frac{M_*}{M_\odot} \leq 0.70$
peak $\sim 0.46 \, M_\odot$ (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 sub-samples (e.g., 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

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mean mass ($M_\odot$)</th>
<th>Median mass ($M_\odot$)</th>
<th>Range of mass (68.3%; $M_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 singles</td>
<td>0.468</td>
<td>0.473</td>
<td>0.437–0.498</td>
</tr>
</tbody>
</table>

Han et al. 2003

Single sdB stars can not be explained only in terms of binary evolution via the merger channel

+ No differences between binaries and single sdB distributions

↓

The (majority of) sdB stars are post-red giant stars

(red giants that have lost most of their envelope)
So, we are back to the problem of extreme mass loss of red giants!

What could cause this extreme mass loss?

- **For binary stars**: ok, thanks to the stellar companion
- **For single stars**, it’s very difficult (internal cause ?)
  + No differences between binaries and single sdB distributions

=> dynamical interactions with **substellar companions** (Soker 98)??

- Geier et al. (2011, 2012): two brown dwarfs orbiting two sdB stars
- Charpinet, Van Grootel et al. (2012, Nature, 480, 496): two close planets orbiting a sdB star
- Schuh et al., Silvotti et al. (in press): 2 BD and 2 planets candidates
Substellar companions for sdB stars

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

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

From asteroseismology (Van Grootel et al. 2010):

- $V = 14.87$, Distance = 1180 pc
- $M = 0.496 \text{ Ms}$, $R = 0.203 \text{ Rs}$
- $T_{\text{eff}} = 27,730 \text{K}$, $\log g = 5.52$
- Age since ZAEHB $\sim 18 \text{ Myr}$

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

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

We have two small planets (comparable to Earth radius) orbiting very close to their host star
A consistent scenario

- Former close-in giant planets (“hot Jupiters”) or brown dwarfs 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.

- Planets and brown dwarfs are responsible of strong mass loss and kinetic energy loss of the progenitor red giant star.

- The star probably left the red giant branch when envelope was too thin to sustain H-burning shell and experienced a delayed He-flash (“hot flasher”).

Figure from Kempton 2011, Nature, 480, 460
IV. Conclusions and Prospects
Conclusions

✓ The formation of sdB stars is a long-standing problem of stellar evolution
✓ From asteroseismology, we can say:
  ✓ sdB stars are post-red giants that have lost most of their envelope
  ✓ no fundamental differences between single and binary sdB stars

✓ A consistent scenario to form single sdB stars: strong mass loss for red giants due to planets and substellar companions?

✓ ~ 7 % of MS stars have close-in giant planets (“hot Jupiters”) that will be engulfed during the red giant phase → such formation from star/planet(s) interaction(s) may be fairly common

Prospects:

✓ Currently only 22 objects: 11 single stars and 11 in binaries
✓ Among > 2000 known sdB, ~100 pulsators are now known
✓ Both light curve modeling and asteroseismology are a challenge (very accurate spectroscopic and photometric observations, stellar models, etc.)