PB 8783: the first sdO star suitable for asteroseismic modeling?

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Plan

1. What are subdwarf B (sdB) and subdwarf O (sdO) stars?
2. Asteroseismology of sdB and sdO stars: state-of-the-art
3. Non-adiabatic asteroseismology of sdB/sdO stars
4. PB 8783: pulsating sdB or sdO star?
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1. **Introduction to sdB and sdO stars**

Evolved, hot ($T_{\text{eff}} = 20,000 - 70,000$ K) and compact ($\log g = 5.2 - 6.2$) stars

**sdB stars**
- Extreme Horizontal Branch stars, core He-burning, extremely thin H-rich envelope
- $p$-mode and $g$-mode pulsators, $\kappa$-mechanism due to Fe-like elements ionization
- About 100 pulsators known in the galactic field, none in globular clusters (GCs)

**sdO stars**
- Mixture of sdB progeny (post-EHB) and post-AGB stars
- 2 pulsators known in the field, 12 in GCs
- Short-period (80-140s), $p$-mode pulsations
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2. Asteroseismology of sdB and sdO stars

- To date: 15 sdB pulsators modeled by asteroseismology

**Mass distribution of sdB stars**

- Access to global and structural parameters ($M_*$, logg, $R_*$, $M_{env}$, $M_{core}$, core composition, etc.)
- Help to clarify the question of **origin** of sdB stars (post-RBG stars having lost most of their H-envelope through binary interaction: stellar, sub-stellar and planet)

**Asteroseismic modeling of sdO pulsators:**
- in GCs: no hope to have good enough photometry for seismology
- in the field: faint ($V\sim15-18$) + difficulties to get accurate Teff (almost all metal lines in UV at these Teff)

Fontaine et al. (2012)
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3. Non-adiabatic asteroseismology of sdB and sdO stars

- Static envelope models with non-uniform Fe abundances (gravitational settling + radiative levitation): l=1 excited pulsations predicted by Cpulse and MAD
3. Non-adiabatic asteroseismology of sdB and sdO stars

- Static envelope models with excited pulsations (Cpulse and MAD)
- Short-period (p-mode) sdB pulsators, i.e. sdBV_r
3. Non-adiabatic asteroseismology of sdB and sdO stars

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- sdO pulsators in Omega Cen
3. Non-adiabatic asteroseismology of sdB and sdO stars

- Static envelope models with excited pulsations (Cpulse and MAD)
- Short-period (p-mode) sdB pulsators, i.e. sdBV_r
- sdO pulsators in Omega Cen
- Field sdO pulsators
3. Non-adiabatic asteroseismology of sdB and sdO stars

Corrected Teff based on UV (HST/COS) spectra: +8,000 K (Latour et al. 2017)
3. Non-adiabatic asteroseismology of sdB and sdO stars

There is also a problem at the period level...
3. Non-adiabatic asteroseismology of sdB and sdO stars

There is also a problem at the period level...

![Graph showing observed periods vs. effective temperature (T_eff) with various labels: log g = 5.9, Fe: 1X, Observed periods.]

Hopefully to be solved with Fe+Ni models:

- Importance of Ni for driving (Jeffery & Saio 2006, Hu et al. 2011, Bloemen et al. 2014)
- Higher ionization T => deeper Z-bump => longer periods
- ready since April 2018 (OPAL monochromatic opacities of Ni), hurray!
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4. PB 8783: sdB or sdO star?

PB 8783 = pulsating subdwarf + F companion

- The second pulsating subdwarf discovered: Koen et al. (1997)
- Frequently re-observed over the years (V=12.6):
  - O’Donoghue et al. (1998), multi-site campaign, 183h data over 15 days
  - Jeffery & Pollacco (2000): pulsations from RV spectroscopy
  - Vuckovic et al. (2005) and Vuckovic et al. (2010): ULTRACAM@WHT in u’g’r’
  - This work: 78d @61”-Mont Bigelow campaign in fall 2007 (Fontaine et al. 2012)

Mt-Bigelow campaign:
- Formal resolution: 0.15µHz
- Noise level: 35 ppm

An old friend of us, always thought to be a sdB star
4. PB 8783: sdB or sdO star?

A very stable pulsation spectrum

<=>: observed multiplets structure

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<tr>
<td>136.269</td>
<td>136.258</td>
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In our Mont Bigelow data (analysis with FELIX, Charpinet et al. 2010):

- 11 additional periods with amplitudes between 4.5 and 6.0σ =>
  **19 independent observed periods in total, 60-190 s**
- Many observed rotational multiplets (1 triplet, 3 quintuplets without central components, and 1 l=4 with 6 components)

**A priori an excellent target for asteroseismology**
4. **PB 8783: sdB or sdO star?**

- Highly contaminated spectrum by the F-companion -> “depollution” procedure needed. Various methods available in spectroscopy...but none is easy to apply and fully convincing here
- Østensen 2012: new medium-resolution spectroscopy @WHT and Mercator, he noticed absence of HeI, and presence of HeII, which is typical of sdO stars

\[ T_{\text{eff}} \approx 50,000 \text{ K} \]
\[ \log g \sim 6 \]
4. PB 8783: sdB or sdO star?

- **Our work:** very high S/N, low-resolution (9Å) spectra (Bok telescope, AZ)
- **Method:** fit to a linear combination of synthetic sdO and F spectra, to minimize $\chi^2$
- **The F-companion dominates:** ~72% of the flux at 660 nm, still >50% at 435 nm
4. PB 8783: sdB or sdO star?

- **Our work**: in summer 2017, we obtained high S/N, very high-resolution (0.1 Å) spectroscopy @UVES/VLT
- **Same analysis method**: $T_{\text{eff}} \sim 52,000$ K, $\log g \sim 5.85$ ($\pm 3000$K and 0.15, ongoing)

We definitely have a sdO star...but to be more accurate and precise, we (desperately) need UV spectra!
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Models:

> 2nd generation models: up to 70,000 K, adapted to sdB and sdO stars
  • static envelope structures; central regions (e.g. convective core) ≡ hard ball
  • include detailed envelope microscopic diffusion (nonuniform envelope Fe abundance),
  • 4 input parameters: $T_{\text{eff}}$, log $g$, $M_*$, envelope thickness log ($M_{\text{env}}/M_*$)

> 3rd and 4th generation models (complete static structures):
only for subdwarf on EHB (core He-burning), not suited for sdO stars

Method: usual forward modeling approach

Fit directly and simultaneously all observed pulsation periods with theoretical ones calculated from sdB models, in order to minimize

$$S^2 = \sum_{i=1}^{N_{\text{obs}}} \left( \frac{P_{\text{obs}}^i - P_{\text{th}}^i}{\sigma_i} \right)^2$$

• Efficient optimization algorithms are used to explore the model parameter space in order to find the minima of $S^2$ i.e. the potential asteroseismic solutions
5. Asteroseismic modeling of PB 8783

- Search parameter space
  - $0.3 \leq \frac{M_*}{M_s} \leq 0.7$ (Han et al. 2002, 2003)
  - $-10.0 \leq \log \left( \frac{M_{\text{env}}}{M_*} \right) \leq -2.5$
  - $\log g$ between 5.7 and 6.1

- $T_{\text{eff}} = 53,000$ K fixed (p-modes are not sensitive to $T_{\text{eff}}$)

- Best fit: $S^2 \sim 3.5$, i.e. $<\Delta P/P> \sim 0.37\%$, $<\Delta P> = 0.4$ s, but non-unique solution
5. Asteroseismic modeling of PB 8783

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\(T_{\text{eff}} = 53,000\) K **fixed** (p-modes are not sensitive to \(T_{\text{eff}}\))

- Best fit: \(S^2 \sim 3.5\), i.e. \(<\Delta P/P> \sim 0.37\%\), \(<\Delta P> = 0.4\) s, **but non-unique solution**

\[M_* = 0.42 \pm 0.03\ M_{\odot}\]
5. Asteroseismic modeling of PB 8783

- Same exercise, but $T_{\text{eff}} = 60,000$ K **fixed** (inspired by Latour et al. 2017)
- Best fit: $S^2 \approx 4.3$, i.e. $\Delta P/P \approx 0.43\%$, $\Delta P = 0.47$ s, but **non-unique solution**

$$M_\ast = 0.486 \pm 0.041 \, M_\odot$$
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Conclusions

Nonadiabatic seismology of sdB/sdO stars
- OK for sdBV_r stars, not for sdOs
- Under-estimation of Teff for sdO stars with optical spectroscopy
- Still a period problem: models with Fe+Ni in the envelope

PB8783
- A priori an excellent target for asteroseismology
- Definitely a sdO pulsator
- But we need UV spectra to get accurate and precise spectroscopic parameters
- (partly) due to this, non-unique asteroseismic solution

Prospects:
✓ “Special” models for sdO, post-EHB stars (He-shell burning)
✓ UV spectroscopy for sdO stars
✓ Using the GAIA distances as constraints (PB 8783: d=911 pc)
✓ Exploitation of the rotational multiplets to get internal rotation profile (PB 8783)