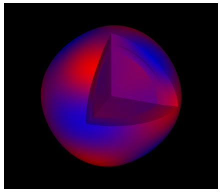
The Sixth Meeting on Hot Subdwarf stars
and Related Objects



Modeling the hot subdwarf star PB 8783 (EO Ceti) by asteroseismology

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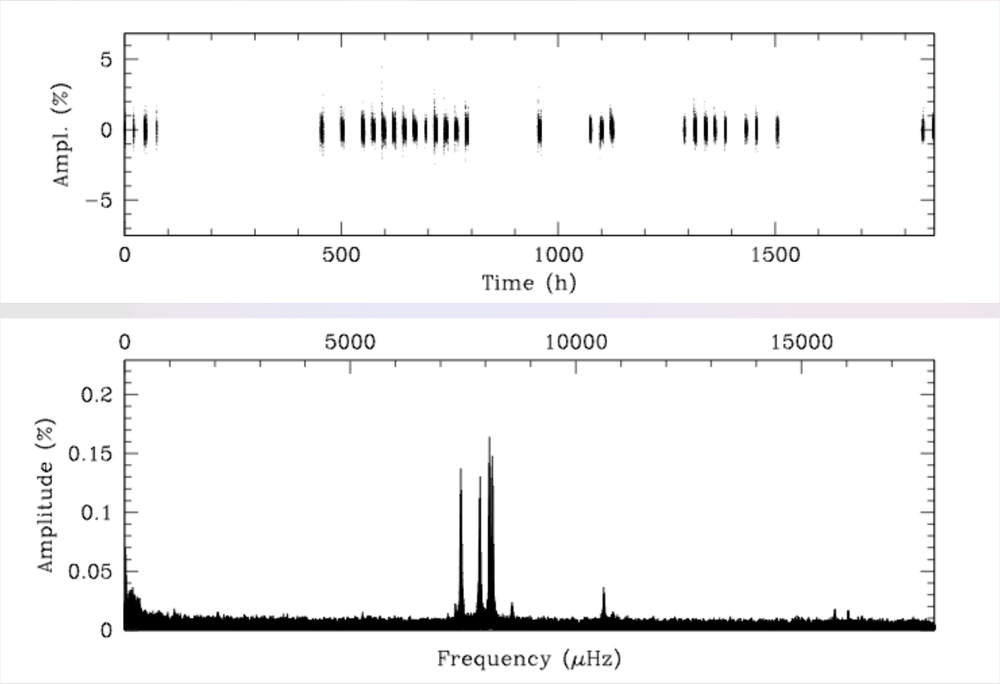
1. Introduction to PB 8783

PB 8783 = pulsating subdwarf + F companion

- Koen et al. (1997) : discovery of a rapidly pulsating sdB star of EC14026 class, with pulsations in the range 122-134 s
- O'Donoghue et al. (1998) (DOD98), multi-site campaign (183h data over 15 days - 1μHz resolution) : 11 pulsation periods 94-136 s, including a triplet @ 122 s (Δv ~ 0.9 μHz)
- Jeffery & Pollacco (2000): pulsations from RV (high-speed spectroscopy ISIS@WHT)
- Vuckovic et al. (2005): 25h @Fick (Iowa) and Vuckovic et al. (2010): ULTRACAM@WHT in u'g'r'
- This work (see Gilles's talk yesterday): 78d @61"-Mont Bigelow campaign in fall 2007



Formal resolution:
0.15μHz
Noise level:
35 ppm

1. Introduction to PB 8783

A relatively stable pulsation spectrum

<>: observed multiplets structure

DOD 1998	Jeffery & Pollacco (2000)	Vuckovic et al. (2005)	Mont Bigelow
94.133	94.118	94.13	94.165
94.454	...	...	94.452
116.418	116.809	116.42	<116.43>
<122.678>	122.835	122.60	<122.680>
123.578	...	123.58	<123.630>
127.060	127.275	127.01	<127.044>
<134.165>	134.120	134.44	<134.169>
136.269	136.258	...	136.273

Plus, in the Bigelow data (analysis with FELIX):

- 11 additional periods with amplitudes between 4.5 and 6.0σ:

  60.97s (4.8), 61.19s (5.8), 62.34s (5.0), 63.52s (6.1), 92.11s (5.0), 92.41s (6.0), 107.62s (5.1), 111.34s (4.5), 122.45s (6.8), 127.45s (4.5), 189.40s (4.5)

- Still ~10 additional periods with amplitudes between 3.8 and 4.5σ

1. Introduction to PB 8783

Many observed close multiplets

Id.	Frequency (μHz)	σ_f (μHz)	Period (s)	σ_P (s)	Amplitude (%)	σ_A (%)	Phase (s)	σ_{Ph} (s)	S/N	Comments
f_{012}	7451.6072	0.0072	134.1992	0.0001	0.0381	0.0034	0.6059	0.0388	11.4	$f_{033} - 2 \times 0.85$ μHz
f_{003}	7452.4599	0.0021	134.1839	0.0000	0.1279	0.0033	0.5589	0.0097	38.4	$f_{033} - 1 \times 0.85$ μHz
f_{033}	7453.3063	0.0145	134.1686	0.0003	0.0189	0.0033	0.3324	0.0657	5.7	$f_{033} \longrightarrow \ell = 2$?
f_{007}	7454.1689	0.0029	134.1531	0.0001	0.0934	0.0033	0.5567	0.0131	27.9	$f_{033} + 1 \times 0.85$ μHz
f_{016}	7455.0223	0.0080	134.1378	0.0001	0.0342	0.0033	0.8519	0.0357	10.2	$f_{033} + 2 \times 0.85$ μHz
f_{014}	7868.0126	0.0089	127.0969	0.0001	0.0352	0.0038	0.7799	0.0363	9.2	$f_{011} - 3\times \sim 1.06$ μHz
f_{010}	7870.1664	0.0064	127.0621	0.0001	0.0488	0.0038	0.4926	0.0257	12.7	$f_{011} - 1\times \sim 1.06$ μHz
f_{011}	7871.2813	0.0066	127.0441	0.0001	0.0475	0.0038	0.1726	0.0318	12.4	$f_{011} \longrightarrow \ell = 4$?
f_{009}	7872.2039	0.0059	127.0292	0.0001	0.0534	0.0038	0.3600	0.0251	13.9	$f_{011} + 1\times \sim 1.06$ μHz
f_{008}	7874.4319	0.0043	126.9933	0.0001	0.0735	0.0038	0.1636	0.0179	19.2	$f_{011} + 3\times \sim 1.06$ μHz
f_{004}	7875.5011	0.0026	126.9760	0.0000	0.1232	0.0038	0.8779	0.0101	32.2	$f_{011} + 4\times \sim 1.06$ μHz
f_{005}	8087.3545	0.0024	123.6498	0.0000	0.1193	0.0035	0.1947	0.0129	33.8	$f - 2 \times 1.10$ μHz
f_{001}	8088.5390	0.0018	123.6317	0.0000	0.1595	0.0035	0.7965	0.0089	45.1	$f - 1 \times 1.10$ μHz
...	...	...	...	...	...	...	...	...	...	$f \longrightarrow \ell = 2$?
f_{027}	8090.7242	0.0142	123.5983	0.0002	0.0203	0.0035	0.1312	0.0600	5.8	$f + 1 \times 1.10$ μHz
f_{019}	8091.8214	0.0092	123.5816	0.0001	0.0315	0.0035	0.3849	0.0386	8.9	$f + 2 \times 1.10$ μHz
f_{002}	8150.6157	0.0020	122.6901	0.0000	0.1456	0.0035	0.0803	0.0120	41.3	
f_{024}	8152.4272	0.0118	122.6629	0.0002	0.0245	0.0035	0.3068	0.0485	7.0	$f_{002} + 1.81$ μHz
f_{034}	8587.2856	0.0153	116.4512	0.0002	0.0186	0.0035	0.4768	0.0635	5.4	$f - 2 \times 0.64$ μHz
f_{029}	8587.9175	0.0142	116.4427	0.0002	0.0200	0.0035	0.4583	0.0581	5.8	$f - 1 \times 0.64$ μHz
...	...	...	...	...	...	...	...	...	...	$f \longrightarrow \ell = 2$?
f_{036}	8589.2125	0.0156	116.4251	0.0002	0.0182	0.0035	0.2085	0.0649	5.3	$f + 1 \times 0.64$ μHz
f_{026}	8589.8491	0.0119	116.4165	0.0002	0.0239	0.0035	0.6697	0.0606	6.9	$f + 2 \times 0.64$ μHz

l=1?

Most probable explanation: rotational multiplets

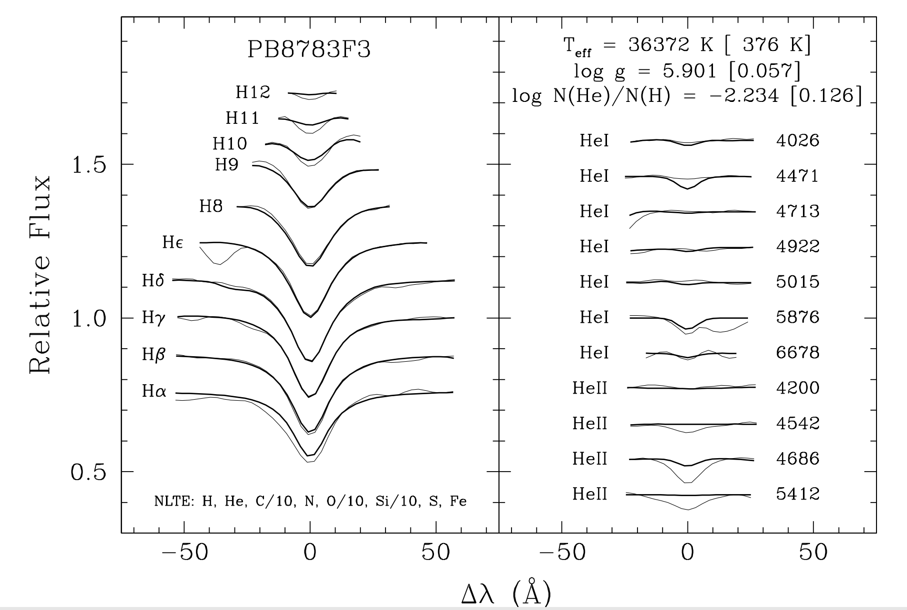
1. Introduction to PB 8783

A sdO or a sdB pulsating star ?

- Highly contaminated spectrum by the F-companion -> "depollution" procedure needed
- Betsy Green: templates of F0-F3 stars -> "cleaned" subdwarf spectrum
- Spectroscopic analysis of Gilles Fontaine (see discussion with him):

« Cool » solution (sdBV)

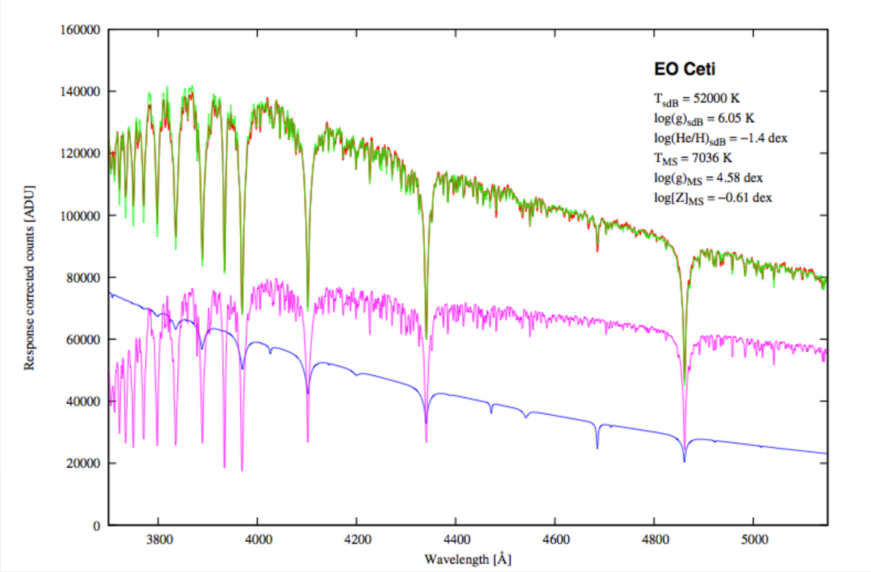
T_{eff}= 36,372 ± 376 K
log g= 5.901 ± 0.057



« Hot » solution (sdOV)

T_{eff} >~ 50,000 K
log g ~ 6.05

Ostensen 2012, sdOB5



2. Models and Method for asteroseismology of hot subdwarfs

2. Asteroseismology of hot subdwarfs

Models:

> 2^{nd} generation models: now up to 70,000 K

- static envelope structures; central regions (e.g. convective core) ≡ hard ball
- include detailed envelope microscopic diffusion (nonuniform envelope Fe abundance), computed by P. Chayer up to 70,000 K
- 4 input parameters : T_{eff}, log g, M_*, envelope thickness log (M_{env}/M_*)

> 3^{rd} generation models: only for subdwarf on EHB

- complete static structures; including detailed central regions description
- include detailed envelope microscopic diffusion (nonuniform envelope Fe abundance)
- input parameters : M_*, log (M_{env}/M_*), log (M_{core}/M_*), X_{core}(C+O) (with C+O+He = 1)

Method: usual forward modeling approach

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

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

- 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

2. Method for asteroseismology

Strategy to model PB 8783

Pulsation spectrum:

- 8 basic periods (common DOD98 and Bigelow):

  94.17s, 116.43s, 122.45s, 122.68s, 123.63s, 127.05s, 134.17s, 136.27s
- 11 additional periods with S/N between 4.5 and 6.0 seen at Bigelow:

  60.97s (4.8), 61.19s (5.8), 62.34s (5.0), 63.52s (6.1), 92.11s (5.0), 92.41s (6.0), 94.45s (4.5), 107.62s (5.1), 111.34s (4.5), 127.45s (4.5), 189.40s (4.5)

Identification constraints from rotational multiplets for 5 modes

116.43s (l ≥ 2), 122.68s (l =1), 123.63s (l=2), 127.05s (l=4), 134.17s (l=2)

⇒ 3 optimization procedures: no constrain on l, weak constraints on l (≥ 1 for multiplets), strong constraints (l imposed for the 5 modes)

1. Modeling PB 8783 as a sdB star

- Both 2G and 3G models are tested

2. Modeling PB 8783 as a sdO star

- 2G models with T_{eff} ~ 50,000 K
- Wide range of log g: 5.80-6.20 (see later)

3. Modeling PB 8783 as a pulsating sdB star

3. Modeling PB 8783 as a sdBV star

« Cool » spectroscopic solution: T_{eff}= 36,372 ± 376 K and log g= 5.901 ± 0.057

- 8 basic periods:

94.17s, 116.43s, 122.45s, 122.68s, 123.63s, 127.05s, 134.17s, 136.27s

- 11 additional periods with S/N between 4.5 and 6.0

Hypotheses:

✓ Search parameter space

- $0.3 \leq M_*/M_s \leq 0.7$ (Han et al. 2002, 2003)
- $-6.0 \leq \log (M_{env}/M_*) \leq -3.5$
- log g between 5.8 and 6.1 (2G)
- $-0.40 \leq \log (M_{core}/M_*) \leq -0.10$ (3G)
- $0 \leq X(C+O) \leq 1$ (3G)

2G: T_{eff}= 36 400 K fixed

3G: under the constraints T_{eff} = 36 400 ± 500 K and log g = 5.91 ± 0.07

✓ No, weak and strong constraints on degree l

I used CALYS, the 320-processors Montreal cluster

3. Modeling PB 8783 as a sdBV star: 8 basic periods

		2G						3G					
Rank or S/N	Period	l	k	fit	l	k	fit	l	k	fit	l	k	fit
		No constraints			Strong			No constraints			Strong		
9.7	94.17	4	3	1%	0	3		1	4		4	3	1.4%
6.9	116.43	2	2		3	2	1%	4	2		2	2	1.2%
6.8	122.45	0	1		0	1	1.8%	0	2		3	1	1.4%
f_2	122.68	4	1		1	2		2	2		1	2	
f_1,f_5	123.63	3	1		2	2	1.2%	1	2		2	1	1.9%
f_4	127.05	2	1		4	1		3	1		4	1	3.0%
f_3,f_7	134.17	1	1	1.2%	2	1	2.5%	0	1	1%	4	0	
5.8	136.27	0	0		1	1	2.9%	2	1	1%	1	1	
$\overline{S^2}$			0.37			2.55			0.37			2.44	
$\overline{\Delta P/P}$			0.54%			1.36%			0.35%			1.15%	
$\overline{\Delta P}$			0.627s			1.729s			0.447 s			1.382 s	
std(ΔP)			0.480s			1.232s			0.522 s			1.121 s	
$T_{\rm eff}$ (K)			36 400			36 400			36 377			36 113	
log g			5.9417			5.9075			5.8894			5.9294	
log q(H)			−4.807			−5.254			-5.7565			−4.7684	
$M_*/M_\odot$			0.513			0.475			0.4790			0.4693	
log q(core)									-0.30			−0.12	
X(C+O)									0.71			0.91	

Comments:

- No, weak (already fulfilled) and strong constraints: similarity of the optimal model, but with a **strong** degradation of the fit quality (some l=3 needed)
- Similarity between optimal 2G and 3G models (even if identification is different)
- Excellent agreement with spectroscopy (log g)

"I like the optimal model, but not the fit"

3. Modeling PB 8783 as a sdBV star: with the 11 additional periods

Only possible to find a model with 17 (=8+9) periods (miss 60.97s & 111.34s)

(strong constraints)

Rank or S/N	Period	l	k	fit	l	k	fit
5.8	61.19(*)	3	7	0.03%	2	7	0.17%
5.0	62.34(*)	2	7	0.27%	4	6	0.55%
6.1	63.52(*)	0	6	0.32%	1	7	0.77%
5.0	92.11(*)	2	4	1.8%	1	4	0.71%
6.0	92.41(*)	1	4	0.98%	4	3	0.63%
9.7	94.17	0	3	0.55%	3	3	1.3%
4.5	94.45(*)	4	3	0.89%	0	3	2.7%
5.1	107.63(*)	4	2	0.50%	3	2	0.46%
6.9	116.43	3	2	1.58%	2	2	0.86%
6.8	122.45	0	1	2.1%	3	1	1.5%
f_2	122.68	1	2	1.4%	1	2	0.24%
f_1, f_5	123.63	2	2	1.3%	2	1	2.03%
f_4	127.05	4	1	1.5%	4	1	2.99%
5.0	127.24(*)	3	1	0.72%	0	1	1.5%
f_3, f_7	134.17	2	1	2.65%	4	0	1.1%
5.8	136.27	1	1	2.2%	1	1	0.36%
4.5	189.40(*)	2	0	0.23%	2	−1	0.48%

	2G Model	3G Model
$\overline{S^2}$	3.256	3.365
$\overline{\Delta P/P}$	1.13%	1.09%
$\overline{\Delta P}$	1.330 s	1.223 s
std(ΔP)	1.052 s	1.015 s
Teff	36 376 K	35 981 K
log g	5.9099	5.9257
log q(H)	−5.1701	−4.8101
$M_*/M_\odot$	0.4795	0.4625
log q(core)		−0.14
X(C+O)		0.918

still poor quality fit

similar emerging 2G and 3G models, and the same as before (with Nper=8)

4. Modeling PB 8783 as a pulsating sdO star

3. Modeling PB 8783 as a sdOV star

Spectroscopy: T_{eff} >~50,000 K, log g~6.05

I've tried to find a solution from 46,000 K to 58,000 K and log g > 6.0:

NO ASTEROSEISMIC SOLUTION

If observed modes are assumed to be low-order p-modes

To account for 122-134s (not so short) as low-order p-modes @ 50,000 K,

I need log g ~5.85

Within the assumption of low-order p-modes:

✓ Search parameter space

- $0.3 \leq M_*/M_s \leq 0.7$ (Han et al. 2002, 2003)
- $-10.0 \leq \log (M_{env}/M_*) \leq -3.5$
- log g between 5.8 and 6.0

T_{eff}= 50,000 K fixed (only 2G models)

4. Modeling PB 8783 as a sdOV star: 8 basic periods

Rank or S/N	Period	l	k	fit
		Strong constraints		
9.7	94.17	0	4	
6.9	116.43	2	2	0.58%
6.8	122.45	4	0	
f_2	122.68	1	2	
f_1, f_5	123.63	2	1	
f_4	127.05	4	−1	
f_3, f_7	134.17	2	0	0.43%
5.8	136.27	4	−2	
S^2		0.853		
$\overline{\Delta P/P}$		0.29%		
$\overline{\Delta P}$		0.361 s		
std(ΔP)		0.200 s		
Teff		50 000 K		
log g		5.8311		
log q(H)		-5.7941		
$M_*/M_\odot$		0.4842		

2 worst fits…

Comments:

- Only strong constraints because of time ☺
- Much better fit than at 36,500 K (1.15% vs 0.29% here !!!)
- No l=3 needed
- log g far from spectroscopic estimate

4. Modeling PB 8783 as a sdOV star: with the 11 additional periods

All well integrated
=> Nper= 19 !

Rank or S/N	Period	l	k	fit
		Strong constraints		
4.8	60.97(*)	1	9	
5.8	61.19(*)	4	8	
5.0	62.34(*)	3	8	
6.1	63.52(*)	0	8	
5.0	92.11(*)	1	5	
6.0	92.41(*)	4	3	
9.7	94.17	0	4	
4.5	94.45(*)	2	3	1.18%
5.1	107.62(*)	3	2	
4.5	111.34(*)	2	2	1.27%
6.9	116.43	3	1	
6.8	122.45	4	0	
f_2	122.68	1	2	
f_1, f_5	123.63	2	1	
f_4	127.05	4	−1	
5.0	127.24(*)	1	1	1.03%
f_3, f_7	134.17	2	0	
5.8	136.27	0	1	
4.5	189.40(*)	1	−1	
S^2		11.1		
$\overline{\Delta P/P}$		0.55%		
$\overline{\Delta P}$		0.638 s		
std(ΔP)		0.668 s		
Teff		50 000 K		
log g		5.8430		
log q(H)		-7.5691		
$M_*/M_\odot$		0.4839		

still very good quality fit

convincing emerging model, and the same as Nper=8

5. Conclusions and prospects

So, PB 8783: a pulsating sdB or sdO star?

- sdB seismic model: (T_{eff}=36,400 K)
  - Excellent agreement with spectroscopy
  - « I like the model, but not the fit »: poor quality if I imposed
  - 2 additional periods with 5σ amplitudes not integrated
- sdO seismic model: (T_{eff}=50,000 K)
  - Poor agreement with spectroscopic log g
  - « I like the model and the fit »: still good quality if I imposed
  - All additional periods well integrated

So, in conclusion: I have a **slight** preference for the sdO model

Prospects:

✓ Is a log g ~ 5.85 (for T_{eff}=50,000 K) possible from spectroscopy?

✓ Confirmation of a sdO star (UV spectroscopic observations with HST)?

✓ Adding the 10 very low-amplitudes modes (<4.5σ) in the seismic analysis

✓ Modeling the observed amplitudes ratios u'g'r' (Vuckovic et al. 2010)

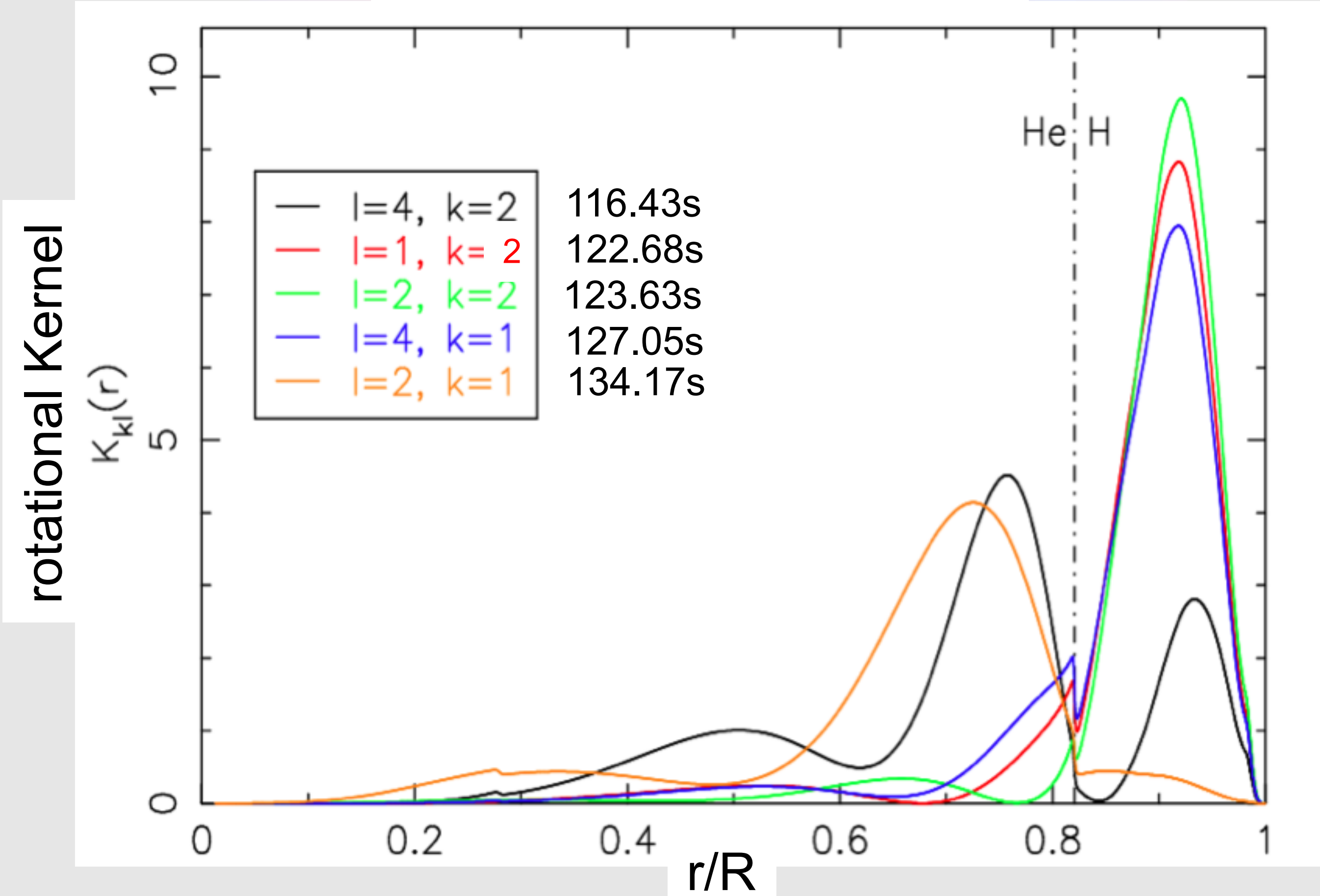
✓ Modeling the internal dynamics (should be close a solid-body rotation)

✓Orbital period of this system? (Jeffery & Pollaco 2000: 0.8-3 d?)

3. Modeling PB 8783 as a sdBV star: Internal dynamics

(work of M. da Silva, my M.Sc. student)

P_{obs} (s)	$\Delta\nu_{obs}$ (μHz)	C_{kl}
122.69	0.91 ± 0.15	0.0167
123.63	1.11 ± 0.15	0.0227
127.04	1.06 ± 0.15	0.0282
134.18	0.85 ± 0.15	0.1267



3. Modeling PB 8783 as a sdBV star: Internal dynamics

Merit function

$$\chi^2 = \frac{1}{N}\sum_{i=1}^{N}\left(\Delta\nu_{obs,i} - \Delta\nu_{th,i}\right)^2$$

Errors

$$\sigma^2_{X,i} = \sum_{j=1}^{N}\left([A^TA]^{-1}A^T\right)^2_{ij}\sigma^2_j$$

where $\sigma_j = 0.15\ \mu\mathrm{Hz}$

$$\Omega = \begin{cases} \Omega_s & \text{if} \quad r/R \gtrsim 0.8 \\ \Omega_i & \text{if} \quad 0.6 \leq r/R \lesssim 0.8 \\ \Omega_c & \text{if} \quad r/R < 0.6 \end{cases}$$

(H/He)

(limits Kkl)

Several rotation laws tested (Ω_c never constrained), most interesting results:

	Rotation law	Ω_s (μHz)	Ω_i (μHz)	Ω_c (μHz)	χ^2
Beck et al. (2012)	Ω_i=Ω_c=10 Ω_s	0.165 ± 0.020	1.65 ± 0.16	1.65 ± 0.16	73.61
differential H/He	Ω_i(=Ω_c) and Ω_s free	1.07 ± 0.11	0.97 ± 0.18	0.97 ± 0.18	0.50
solid body	Ω_i=Ω_c= Ω_s	1.04 ± 0.08	1.04 ± 0.08	1.04 ± 0.08	1.18

Close to a solid-body rotation (at least for r/R > 0.6) of 11.1 d

Slight differential rotation H/He (with a faster envelope)?

1. Introduction to PB 8783

A relatively stable pulsation spectrum

Pulsation spectrum:

- 8 basic periods (common DOD98 and Bigelow):

  94.17s, 116.43s, 122.45s, 122.68s, 123.63s, 127.05s, 134.17s, 136.27s
- 11 additional periods with S/N between 4.5 and 6.0 seen at Bigelow:

  60.97s (4.8), 61.19s (5.8), 62.34s (5.0), 63.52s (6.1), 92.11s (5.0), 92.41s (6.0), 94.45s (4.5), 107.62s (5.1), 111.34s (4.5), 127.45s (4.5), 189.40s (4.5)
- Still ~10 additional periods with S/N between 3.8 and 4.5