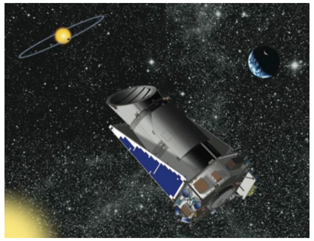
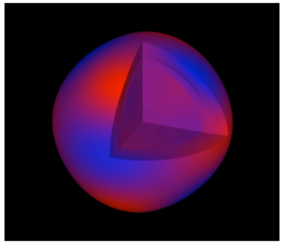


Third Kepler Asteroseismology Workshop
Århus June 2010



Structural and core parameters of the hot B subdwarf KPD 1943+4058 as inferred from g-mode oscillations

Valerie Van Grootel[1]

S. Charpinet[1], G. Fontaine[2], P. Brassard[2], E.M. Green[3], S.K. Randall[4], and WG11 and Kepler collaborators

(1) Laboratoire d'Astrophysique de Toulouse, France
(2) Université de Montréal, Canada
(3) University of Arizona, USA
(4) European Southern Observatory, Germany

Outline

1. Introduction to subdwarf B (sdB) stars
2. Models and Method for sdB stars asteroseismology
3. Observations of KPD 1943+4058
4. Asteroseismic analysis
5. Conclusion and Prospects

1. Introduction to sdB stars

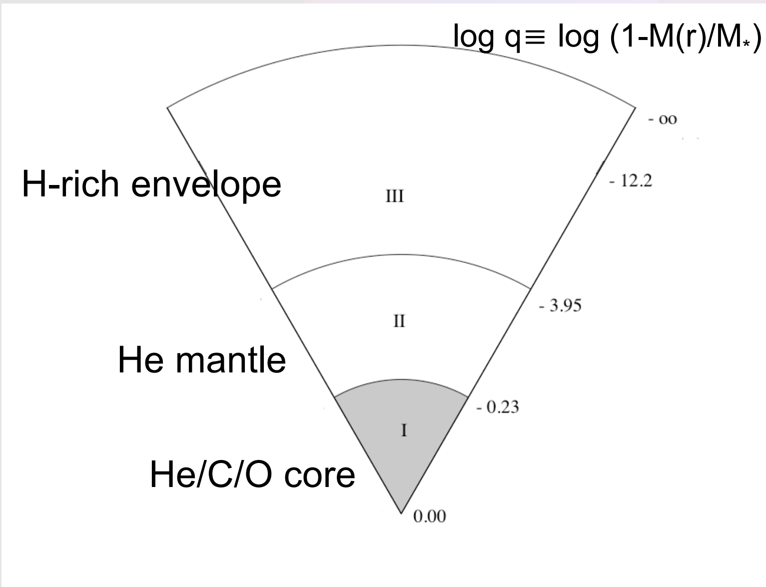
Hot (T_{eff} = 20 000 - 40 000 K) and compact (log g = 5.2 - 6.2) stars belonging to Extreme Horizontal Branch (EHB)

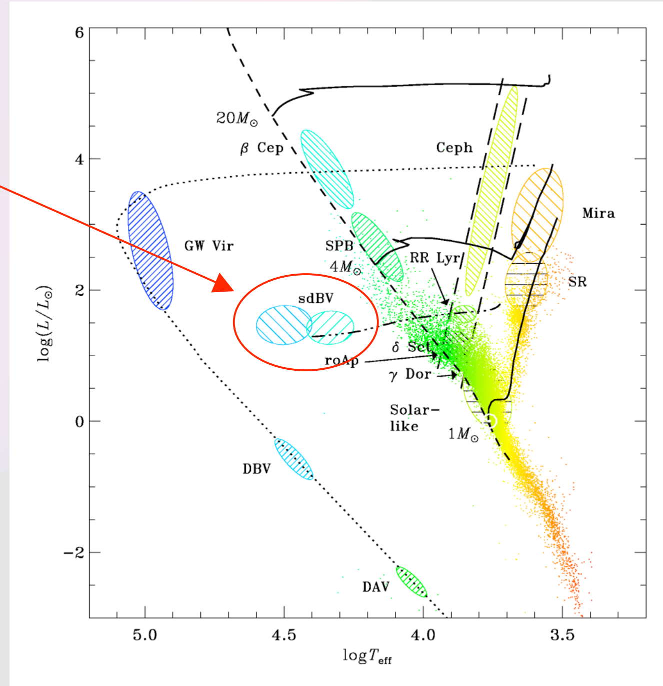
- convective He-burning core (I), radiative He mantle (II) and very thin H-rich envelope (III)
- $M_* = M_{core} + M_{env} \sim 0.5\ M_{sun}$; single or binary formation scenarios still unclear
- lifetime of ~ 10^8 yr (100 Myr) on EHB, then evolve as low-mass white dwarfs

Two classes of multi-periodic sdB pulsators (V ~ 12-16)

> 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 !





2. Models and Method for sdB asteroseismology

New generation of sdB models

(needed for g-mode pulsations computation)

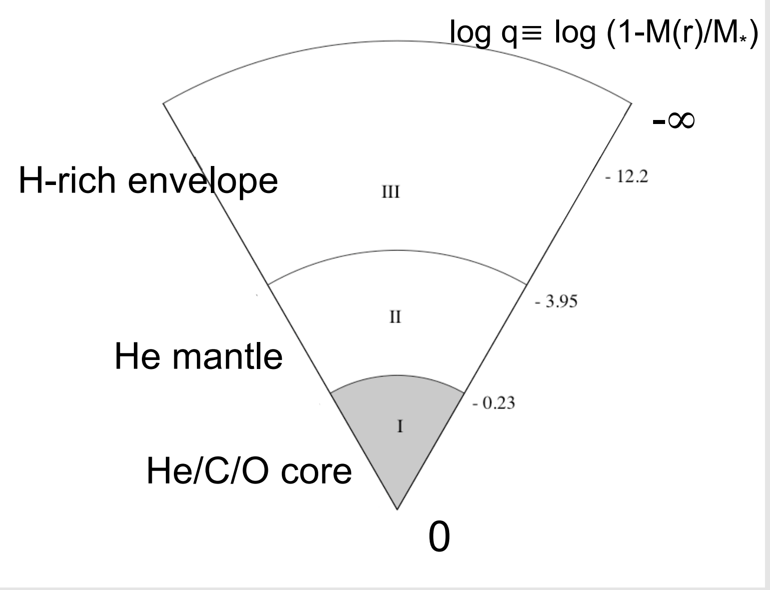
- complete static structures; including detailed central regions description
- include detailed envelope microscopic diffusion (nonuniform envelope Fe abundance)
- input parameters:
  - total mass M_*,
  - envelope thickness $\log (M_{env}/M_*)$
  - core size $\log (1-M_{core}/M_*)$
  - core composition He/C/O (under constraint C+O+He = 1)

With these models,

T_{eff} and log g are computed a posteriori

⇒

Atmospheric parameters from spectroscopy are integrated as external constraints for seismic analysis



The forward modeling approach

The principle:

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

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

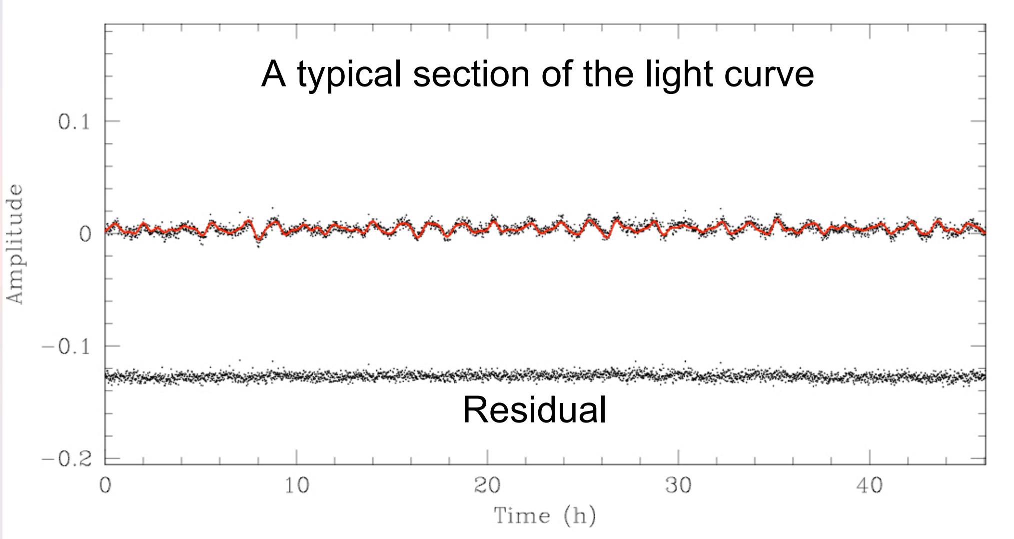
- Efficient optimization codes (based on Genetic Algorithms) are used to explore the vast model parameter space in order to find the minima of S^2, i.e. the potential asteroseismic solutions
- The S^2 is degraded if the computed T_{eff}/logg fall outside 3-σ spectroscopic errors (this is to incorporate spectroscopic constraints in the optimization procedure)

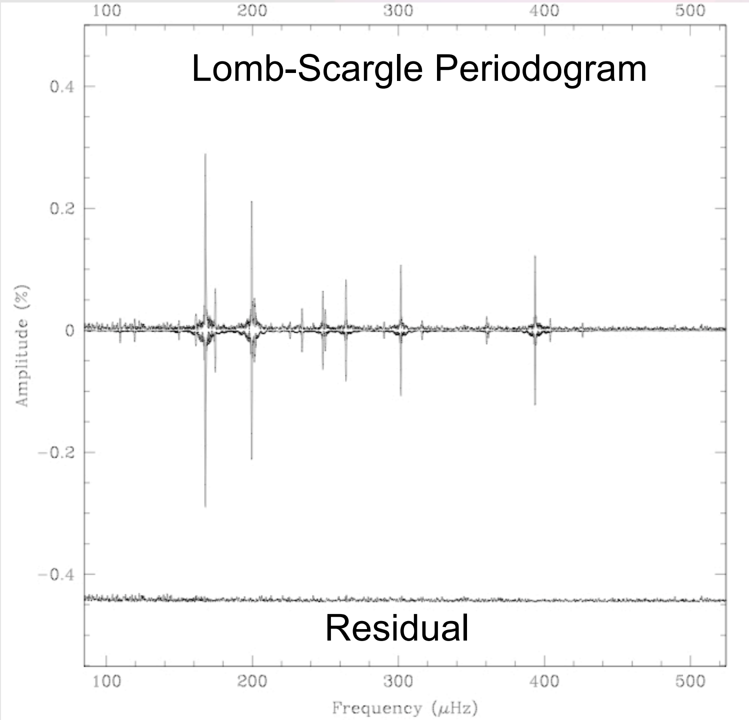
Results:

- Identification of the pulsation modes (with or without external constraints)
- Structural and core parameters of the star (M_*, envelope thickness, core size etc.)

3. Observations of KPD 1943+4056 (KIC 005807616)

Observed in white light photometry by *Kepler* during the Q2.3 survey phase (27.1 d) at short cadence (58.85 s)





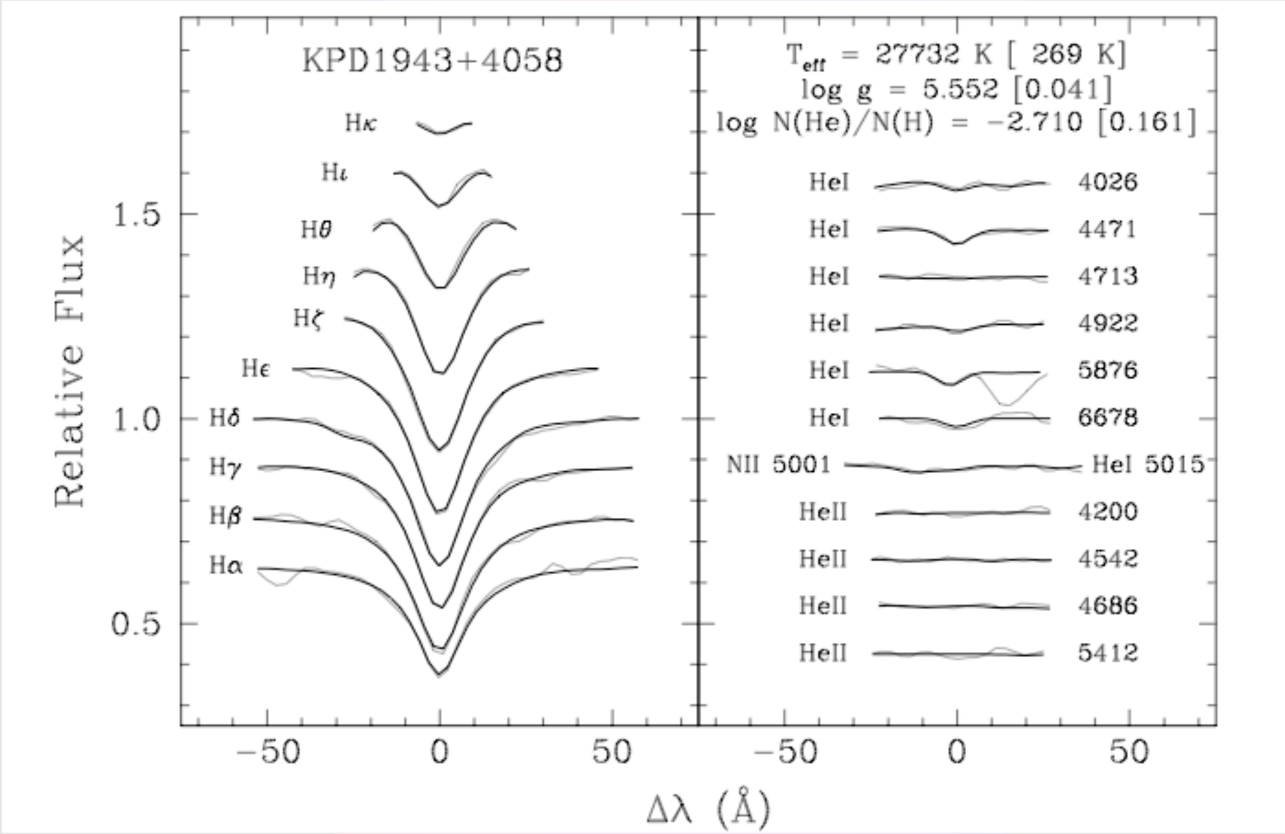
Frequency extraction using prewithening:

- 26 g-type periods with amplitudes above 4-σ in the range 2300 - 9200 s
- 14 additional periods between 3.2 and 4-σ (σ is the local noise level)

3. Observations of KPD 1943+4056

Atmospheric parameters from spectroscopy

Low-resolution (9Å), moderately high S/N (~112 in the blue) 2.3-m Kitt Peak spectrum



C (1/10 solar)
N (solar)
O (1/10 solar)
Si (1/10 solar)
S (solar)
Fe (solar)

⇑

NLTE model atmospheres *with* heavy metals abundances "à la Blanchette et al. (2008)":

T_{eff} = 27 730 ± 270 K
log g = 5.552 ± 0.041

4. Asteroseismic analysis

Search the model(s) whose $\sigma_{kl,m=0}$ theoretical periods best fit the observed ones

> Some very-close peaks among the 26 periods above 4σ, for an unclear reason (slow star rotation yet unresolved, amplitude changes, etc.)

$\Rightarrow$ 18 well-secured independent periods remaining for the seismic analysis

> Optimization procedure hypotheses:

- Search parameter space:
  - $0.30 \leq M_*/M_s \leq 0.70$ (Han et al. 2002, 2003)
  - $-5.0 \leq \log (M_{env}/M_*) \leq -1.8$
  - $-0.40 \leq \log (1-M_{core}/M_*) \leq -0.10$ (Dorman et al. 1993)
  - $0 \leq X(C+O) \leq 0.99$

  Under the constraints (3-σ uncertainties) from spectroscopy

  T_{eff} = 27 730 ± 810 K and log g = 5.552 ± 0.123

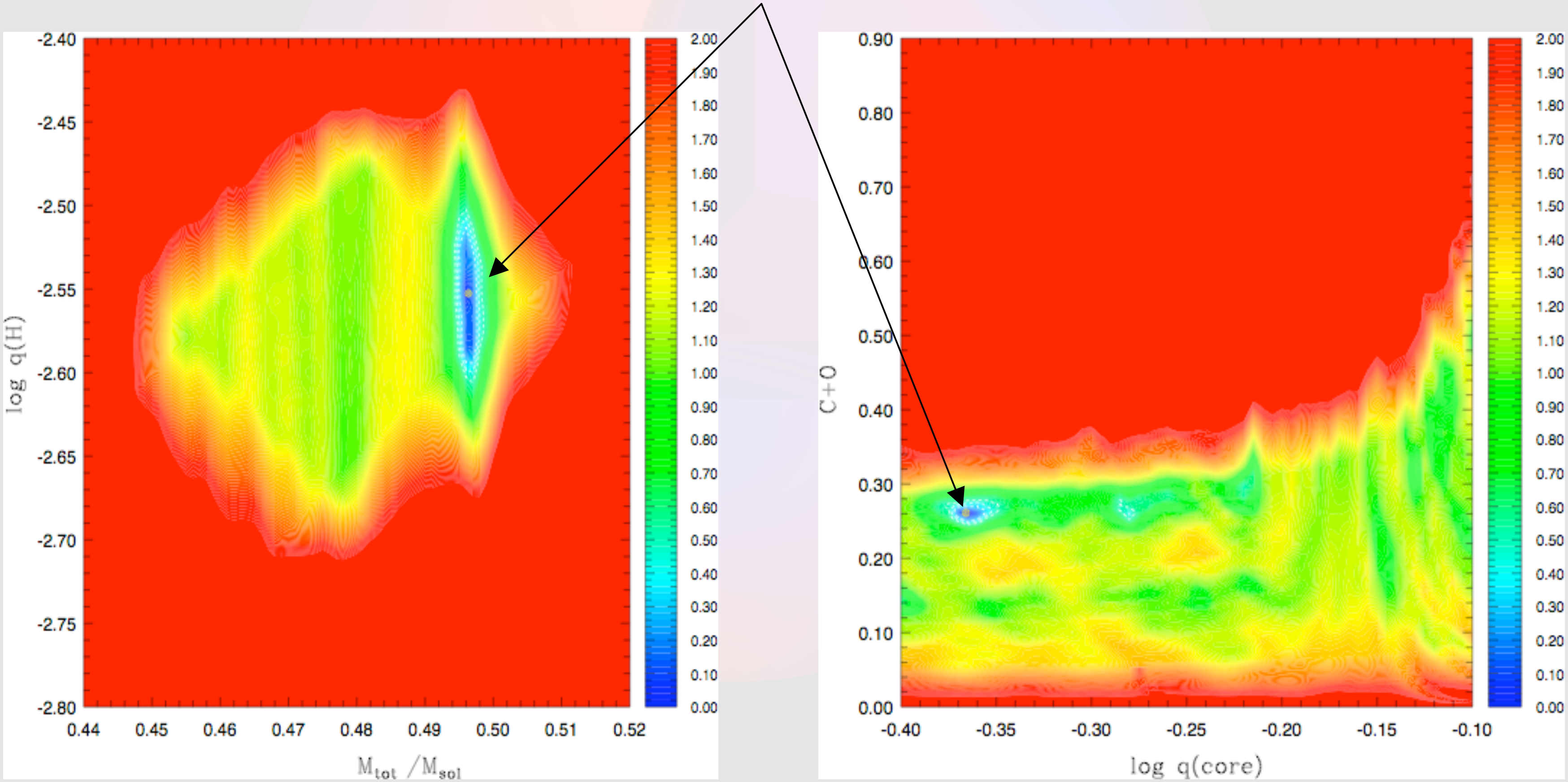
- Computation of all theoretical modes l=1 and 2 in the range 2000–9500 s (no assumption on mode identification)

4. Asteroseismic analysis

A clear model emerges in the optimization procedure: ($\Delta X/X \sim 0.22\%$)

- $M_* = 0.4964\ M_s$
- $\log (M_{env}/M_*) = -2.553$
- $\log (1-M_{core}/M_*) = -0.366$
- $X(C+O) = 0.26$; $X(He) = 0.74$

$T_{eff} = 28\ 050$ K
$\log g = 5.524$



4. Asteroseismic analysis

Period fit and mode identification (extract)

Excellent fit to the 18 well-secured observed periods:
$\overline{\Delta X/X}$~ 0.22% (or $\overline{\Delta P}$~ 7.8 s or $\overline{\Delta \nu}$~ 0.7 μHz, with a standard deviation of 4.6 s)

ℓ	k	ν_{obs} (μHz)	ν_{th} (μHz)	P_{obs} (s)	P_{th} (s)	$\log E$ (erg)	C_{kl}	$\Delta X/X$ (%)	ΔP (s)	$\Delta\nu$ (μHz)	ID
1	-3	...	1071.115	...	933.61	45.985	0.5956	...	...	...	
1	-4	[824.935]	826.453	[1212.22]	1209.99	47.384	0.4579	[+0.18]	[+2.23]	[−1.518]	[u_6]
1	-5	...	661.624	...	1511.43	47.791	0.4550	...	...	...	
1	-8	...	454.406	...	2200.68	45.448	0.4829	...	...	...	
1	-9	393.611	392.554	2540.58	2547.42	46.382	0.4886	−0.27	−6.84	+1.056	f_3
1	-10	...	339.627	...	2944.40	45.669	0.4887	...	...	...	
1	-11	316.192	316.229	3162.63	3162.26	44.671	0.4761	+0.01	+0.37	−0.037	f_{20}
1	-12	...	303.633	...	3293.45	45.114	0.4830	...	...	...	
1	-13	...	285.164	...	3506.75	44.966	0.4896	...	...	...	
1	-14	264.090	263.502	3786.58	3795.04	44.207	0.4881	−0.22	−8.46	+0.589	f_6
1	-15	[249.917]	249.161	[4001.33]	4013.47	44.045	0.4895	[−0.30]	[−12.14]	[+0.756]	[f_{12}]
1	-16	...	232.938	...	4292.99	43.675	0.4885	...	...	...	
1	-17	...	222.751	...	4489.32	43.848	0.4926	...	...	...	
1	-18	...	208.197	...	4803.15	44.041	0.4938	...	...	...	
1	-19	199.497	199.774	5012.60	5005.66	43.623	0.4900	+0.14	+6.94	−0.276	f_2
1	-20	...	194.167	...	5150.20	43.960	0.4928	...	...	...	
1	-21	...	184.491	...	5420.33	44.301	0.4956	...	...	...	
1	-22	174.627	174.300	5726.49	5737.25	43.808	0.4945	−0.19	−10.75	+0.327	f_7
1	-23	...	168.679	...	5928.44	43.545	0.4928	...	...	...	
1	-24	161.303	161.415	6199.51	6195.20	43.942	0.4963	+0.07	+4.31	−0.112	f_{13}
1	-25	...	154.281	...	6481.70	43.687	0.4959	...	...	...	
1	-26	...	149.249	...	6700.20	43.428	0.4949	...	...	...	
1	-27	[144.441]	143.934	[6923.24]	6947.63	43.477	0.4957	[−0.35]	[−24.39]	[+0.507]	[u_2]
1	-28	...	139.036	...	7192.36	43.284	0.4953	...	...	...	
1	-35	...	112.753	...	8868.97	43.019	0.4971	...	...	...	
1	-36	109.572	109.489	9126.39	9133.36	43.174	0.4975	−0.08	−6.97	+0.084	f_{15}
1	-37	...	106.951	...	9350.06	42.917	0.4969	...	...	...	

- l=1 & 2, k=–9 to –58 g-modes
- About left-aside periods: need better resolution data to evaluate their origin
- About the 14 additional periods (between 3.2 and 4σ):
  - 13 of them as l=1 & 2 modes
  - need *one* l=4 mode for u_{12} at 3.8σ (the most visible in sdBs after l=1 & 2)

4. Asteroseismic analysis

Comments on core and structural parameters

	Quantity	Estimated Value		
	$T_{\rm eff}$ (K)	27730	$\pm$	270 [a]
		28050	$\pm$	470 [b]
	$\log g$	5.552	$\pm$	0.041 [a]
		5.520	$\pm$	0.029 [b]
Primary parameters	$M_*/M_\odot$	0.4964	$\pm$	0.0013
	$\log(M_{\rm env}/M_*)$	-2.552	$\pm$	0.070
	$\log(1-M_{\rm cc}/M_*)$	-0.366	$\pm$	0.010
	$M_{\rm cc}/M_\odot$	0.281	$\pm$	0.011
	$X_{\rm core}$(C+O)	0.2612	$\pm$	0.0080
Secondary parameters	Age (Myr)	18.4	$\pm$	1.0
	$R/R_\odot$ (M_*, g)	0.2026	$\pm$	0.0070
	$L/L_\odot$ ($T_{\rm eff}$, R)	22.92	$\pm$	3.13
	M_V (g, $T_{\rm eff}$, M_*)	4.21	$\pm$	0.11
	$E(B-V)$	0.094	$\pm$	0.017
	d (V, M_V) (pc)	1183	$\pm$	93

$T_{\rm eff}$ and $\log g$: Excellent consistency with spectroscopic estimates (which was not guaranteed a priori!)

$M_*/M_\odot$ → Close to canonical value expected for sdBs

$\log(M_{\rm env}/M_*)$ → Rather thick envelope

(a): from spectroscopy

(b): from asteroseismology

4. Asteroseismic analysis

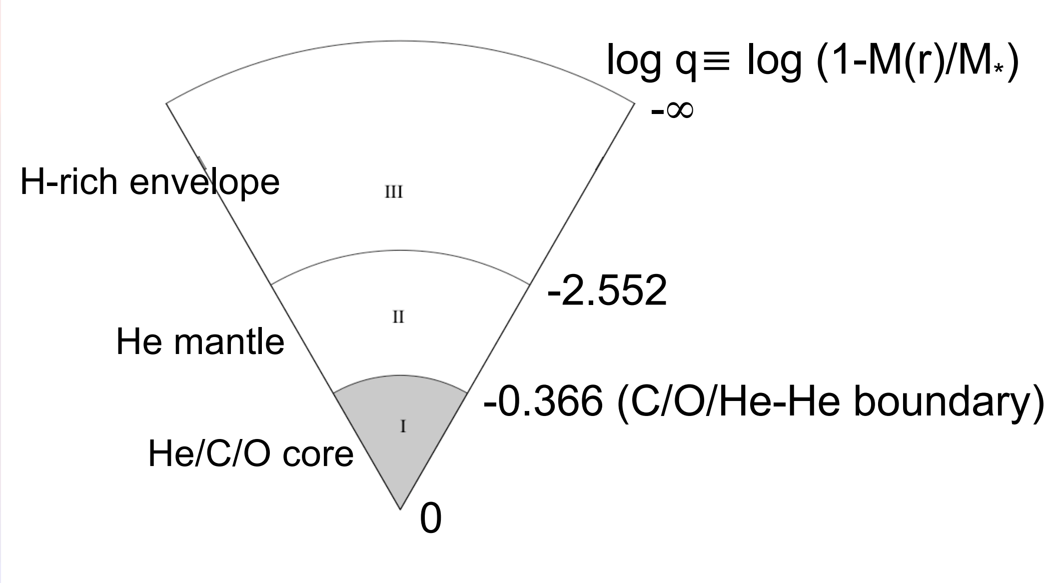
Comments on core and structural parameters

	Quantity	Estimated Value
	$T_{\rm eff}$ (K)	27730 ± 270 [a]
		28050 ± 470 [b]
	$\log g$	5.552 ± 0.041 [a]
		5.520 ± 0.029 [b]
Primary parameters	$M_*/M_\odot$	0.4964 ± 0.0013
Primary parameters	$\log(M_{\rm env}/M_*)$	−2.552 ± 0.070
Primary parameters	$\log(1 - M_{\rm cc}/M_*)$	−0.366 ± 0.010
Primary parameters	$M_{\rm cc}/M_\odot$	0.281 ± 0.011
Primary parameters	$X_{\rm core}$(C+O)	0.2612 ± 0.0080
Secondary parameters	Age (Myr)	18.4 ± 1.0
Secondary parameters	$R/R_\odot$ (M_*, g)	0.2026 ± 0.0070
Secondary parameters	$L/L_\odot$ ($T_{\rm eff}$, R)	22.92 ± 3.13
Secondary parameters	M_V (g, $T_{\rm eff}$, M_*)	4.21 ± 0.11
Secondary parameters	$E(B-V)$	0.094 ± 0.017
Secondary parameters	d (V, M_V) (pc)	1183 ± 93

(a): from spectroscopy

(b): from asteroseismology

This is the first time we can probe the core of sdBs from asteroseismology !



• Size of convective core from Schwarzschild criterion (e.g. Dorman et al. 1993): log q ~ -0.20
overshooting signature ?

• Age of the sdB since ZAEHB, from comparison with evolutionary models: 18.4 Myr

5. Conclusion and Prospects

Conclusion: Thanks to *Kepler*, we have for the first time

- high-quality data of long-period, g-modes sdB stars
- a full asteroseismic analysis of a long-period sdB star, leading to the determination of structural and core parameters
- used g-mode seismology for a core-helium burning star, representative of all horizontal branch stars.

Prospects:

- for KPD 1943+4058:
  - *Kepler* observations with 3-month baseline
  - origin of the unresolved close frequencies detected here with 27-day baseline ?
  - Determination of the core dynamics (this would be the first time for a single sdB star) ?
- Already dozens of short- and long-period (and hybrid !) pulsating sdB stars discovered by *Kepler*, which are waiting for seismic modeling…