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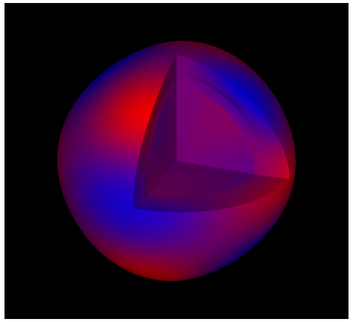


Probing the cores of Extreme Horizontal Branch stars by gravity-mode seismology

the case of KPD 0629-0016 observed with CoRoT

Valerie Van Grootel[(1)]

S. Charpinet[(2)], G. Fontaine[(3)], P. Brassard[(3)], E.M. Green[(4)],
and CoRoT collaborators

(1) Institut d'Astrophysique, Université de Liège, Belgium
(2) IRAP, Toulouse, France
(3) Université de Montréal, Canada
(4) University of Arizona, USA

1. Introduction to subdwarf B (sdB) stars

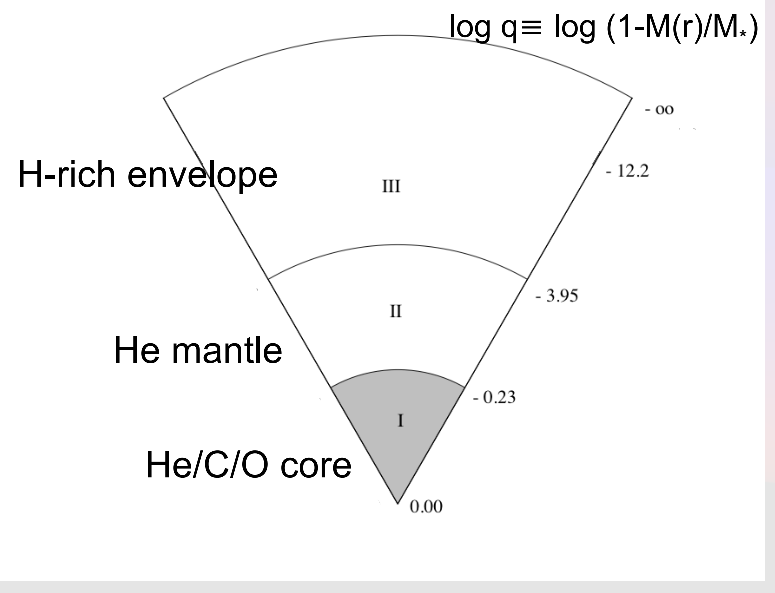
Hot (T_{eff} = 20 000 - 40 000 K) and compact (log g = 5.2 - 6.2) stars belonging to Extreme Horizontal Branch (EHB)

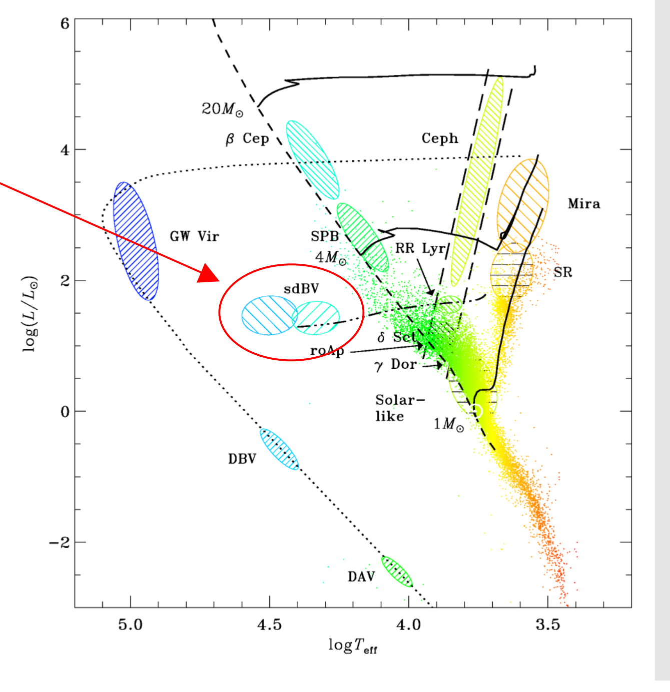
- convective He-burning core (I), radiative He mantle (II) and very thin H-rich envelope (III)
- $M_* \sim 0.5\ M_{sun}$; single or binary formation scenarios still unclear
- lifetime of ~ 100 Myr on EHB, then evolve as low-mass white dwarfs

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)

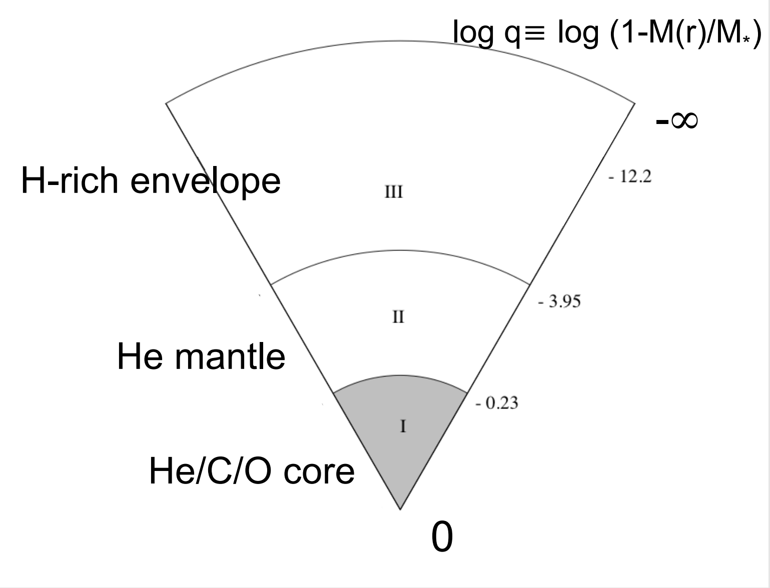
- complete static structures; including detailed central regions description
- include detailed envelope microscopic diffusion (nonuniform envelope Fe abundance)
- input parameters:
  - total mass M_*,
  - envelope thickness $\log (M_{env}/M_*)$
  - core size $\log (1-M_{core}/M_*)$
  - core composition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

With these models,

T_{eff} and log g are computed a posteriori

$\Rightarrow$

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



2. Models and Method for sdB asteroseismology

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

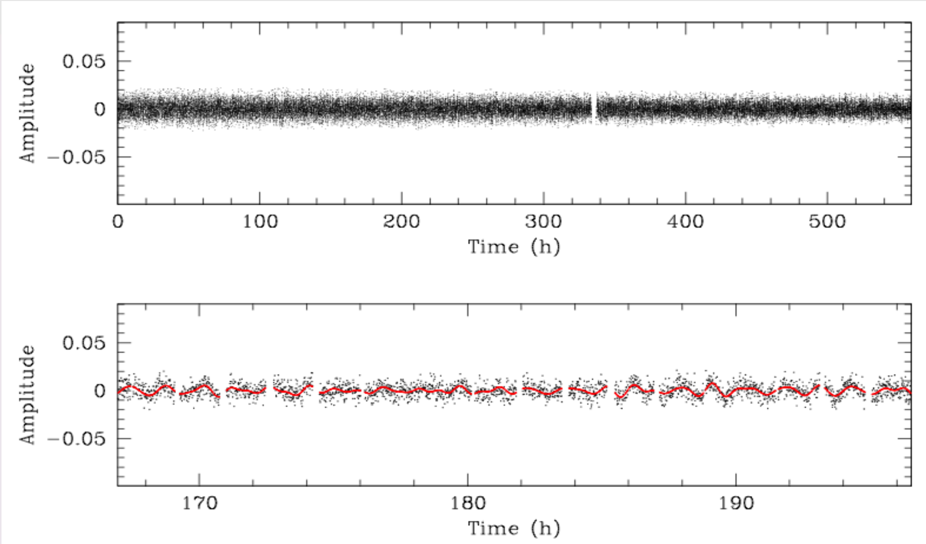
$$S^2 = \sum_{i=1}^{N_{\rm obs}} \left(P_{\rm obs}^i - P_{\rm th}^i \right)^2$$

- 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)

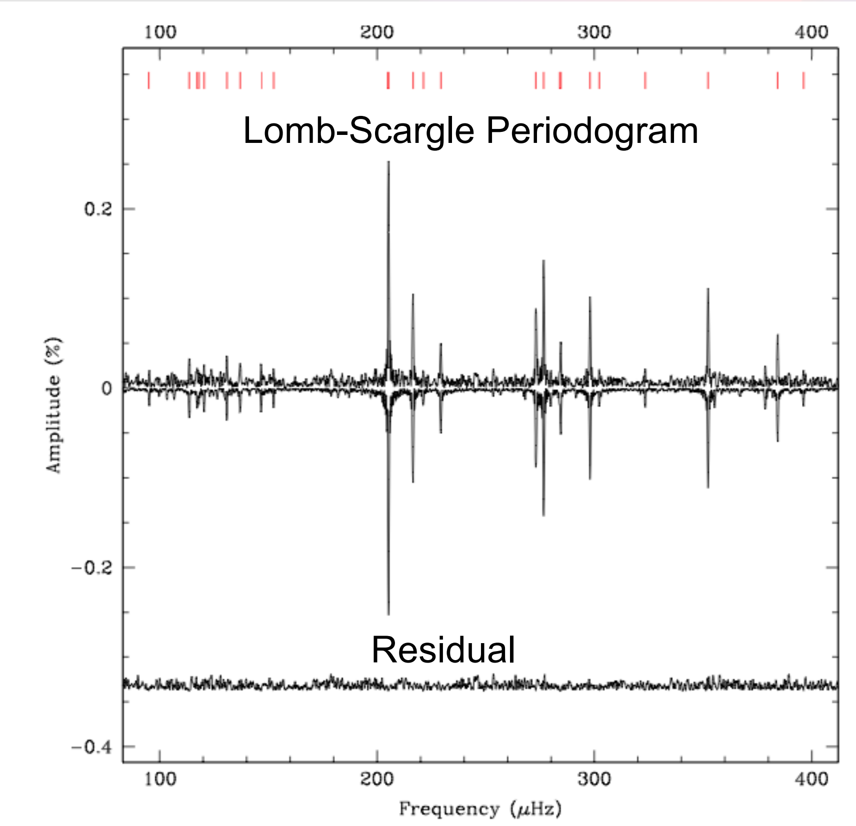
Results:

- 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 0629-0016 (V = 14.9)



Observed in white light photometry by *CoRoT* during the SRa03 (23.3 d) in March 2010 with T_{exp} = 32 s



Frequency extraction using prewithening:

- 17 g-type periods with amplitudes above 4-σ in the range 2500 - 10500 s
- 7 additional periods between 3.6 and 4-σ (σ is the local noise level)
- mean noise level: 57 ppm

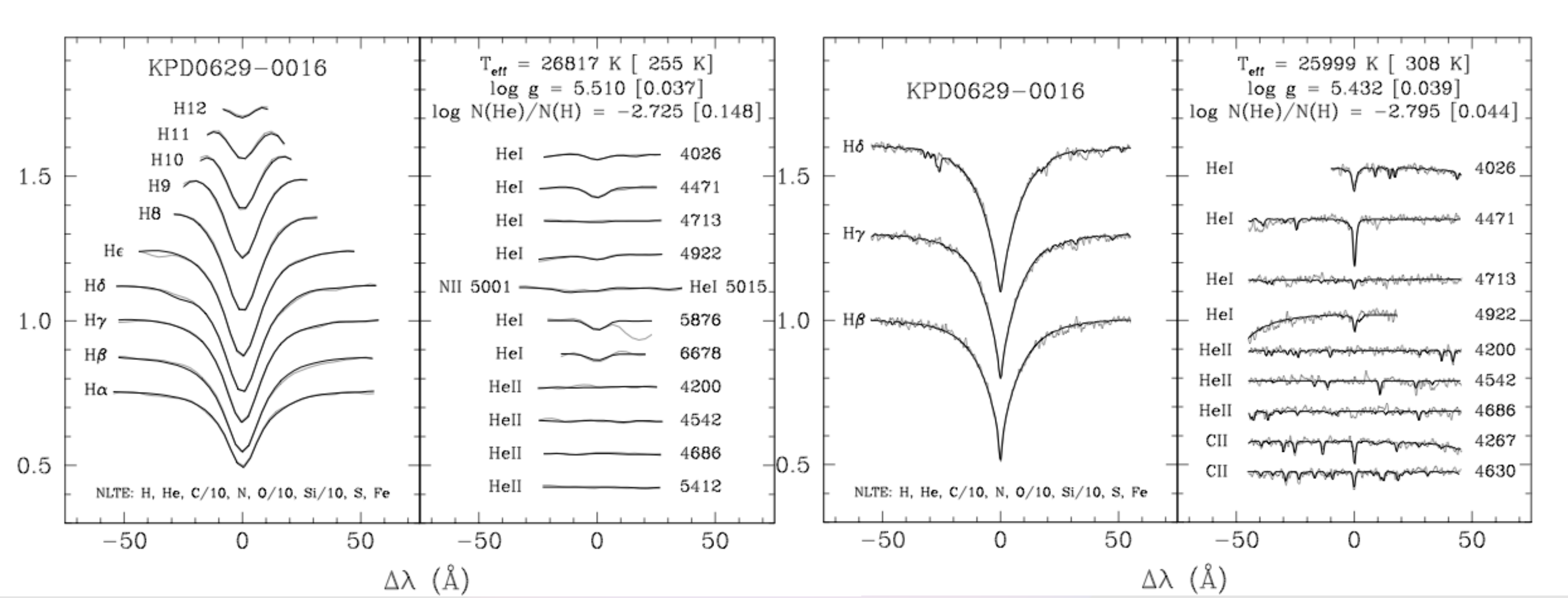
(Charpinet et al. 2010, A&A, 516, L6)

3. Observations of KPD 0629-0016

Atmospheric parameters from spectroscopy

Low-resolution (9Å), S/N ~ 310
2.3-m Kitt Peak spectrum

Mid-resolution (1Å), S/N ~ 75
6-m MMT spectrum



NLTE model atmospheres *with* heavy metals abundances “à la Blanchette et al. 2008” (1/10 solar: C,O,Si - solar: N,S,Fe): T_{eff} = 26 484 ± 200 K and log g = 5.473 ± 0.027

4. Asteroseismic analysis

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

> 18 well-secured independent periods above or equal to 4σ for the seismic analysis

> see a posteriori how additional periods (3.2 - 3.8σ) can be interpreted

> Optimization procedure hypotheses:

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

  Under the constraints (3-σ uncertainties) from spectroscopy

  $T_{eff} = 26\,484 \pm 600$ K and $\log g = 5.473 \pm 0.123$

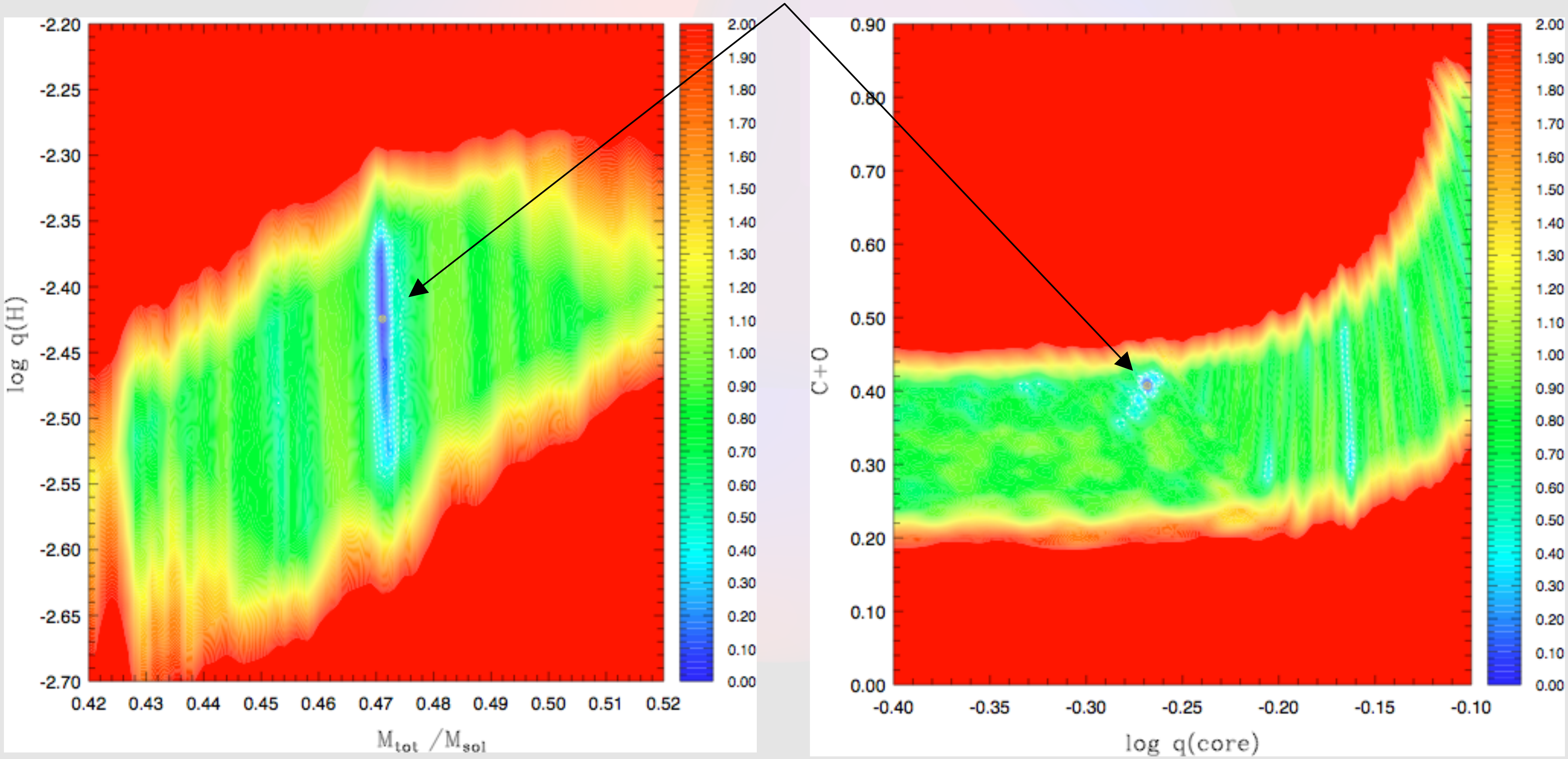
- Computation of all theoretical modes l=1 and 2 in the range 2500−10650 s (no assumption on mode identification)

4. Asteroseismic analysis

A clear model emerges in the optimization procedure: ($\Delta X/X \sim 0.23\%$)

- $M_* = 0.4711\ M_s$
- $\log (M_{env}/M_*) = -2.424$
- $\log (1-M_{core}/M_*) = -0.269$
- $X(C+O) = 0.41$; $X(He) = 0.59$

$T_{eff} = 26\ 290$ K
$\log g = 5.450$



4. Asteroseismic analysis

Period fit and mode identification (extract)

Excellent fit to the 18 well-secured observed periods:
$\overline{\Delta X/X}$~ 0.23% (or $\overline{\Delta P}$~ 11.7 s or $\overline{\Delta \nu}$~ 0.53 μHz, with a standard deviation of 7.7 s)

ℓ	k	$\nu_{\rm obs}$ (μHz)	$\nu_{\rm th}$ (μHz)	$P_{\rm obs}$ (s)	$P_{\rm th}$ (s)	$\Delta X/X$ (%)	ΔP (s)	$\Delta\nu$ (μHz)	ID
1	−9	384.332	384.172	2601.91	2603.00	−0.04	−1.08	+0.16	f_7
1	−10	...	341.035	...	2932.25	...	...	...	
1	−11	323.352	322.695	3092.60	3098.91	−0.20	−6.30	+0.658	u_7
1	−12	298.009	297.466	3355.60	3361.72	−0.18	−6.12	+0.543	f_5
1	−13	276.653	277.546	3614.64	3603.01	+0.32	+11.63	−0.893	f_2
1	−14	...	265.392	...	3768.02	...	...	...	
1	−18	...	215.624	...	4637.71	...	...	...	
1	−19	205.289	205.204	4871.19	4873.20	−0.04	−2.01	+0.085	f_1
1	−20	...	199.236	...	5019.17	...	...	...	
1	−25	...	158.446	...	6311.28	...	...	...	
1	−26	[152.379]	152.704	[6562.60]	6548.64	[+0.21]	[+13.96]	[−0.325]	[u_4]
1	-27	146.616	146.494	6820.56	6826.23	−0.08	−5.68	+0.122	f_{15}
1	−28	...	141.851	...	7049.65	...	...	...	
1	−29	136.966	137.201	7301.08	7288.56	+0.17	+12.51	−0.235	f_{13}
1	−32	...	124.927	...	8004.68	...	...	...	
1	−33	120.415	120.731	8304.59	8282.91	+0.26	+21.68	−0.315	f_{14}
1	−34	177.966	177.599	8477.01	8503.49	−0.31	−26.48	+0.367	f_{16}
1	−35	...	114.420	...	8739.71	...	...	...	
2	−17	[396.191]	391.954	[2524.04]	2551.32	[−1.08]	[−27.28]	[+4.237]	[u_3]
2	−18	...	370.111	...	2701.89	...	...	...	
2	−19	352.292	353.294	2838.56	2830.51	+0.28	+8.05	−1.002	f_3
2	−23	[302.222]	299.272	[3308.82]	3341.45	[−0.99]	[−32.62]	[+2.951]	[u_6]
2	−24	284.585	286.067	3513.89	3495.69	+0.52	+18.20	−1.482	f_9
2	−25	273.074	273.962	3662.01	3650.14	+0.32	+11.87	−0.888	f_6

- l=1 & 2, k=−9 to −74 g-modes

- About the additional periods (between 3.6 and 3.8σ):
  - 6 of them as l=1 & 2 modes
  - need *one* l=4 mode for u_5 at 3.8σ (the most visible in sdBs after l=1 & 2)

4. Asteroseismic analysis

Comments on core and structural parameters

	Quantity	Estimated Value
Primary parameters	$T_{\rm eff}$ (K)	$26\,484 \pm 196$[1]
		$26\,290 \pm 530$[2]
	$\log g$	5.473 ± 0.027[1]
		5.450 ± 0.034[2]
	$M_*/M_\odot$	0.471 ± 0.002
	$\log(M_{\rm env}/M_*)$	-2.42 ± 0.07
	$\log(1 - M_{\rm core}/M_*)$	-0.27 ± 0.01
	$M_{\rm core}/M_\odot$	0.22 ± 0.01
	$X_{\rm core}$(C+O)	0.41 ± 0.01
Secondary parameters	Age (Myr)	42.6 ± 1.0[3]
	$R/R_\odot$ (M_*, g)	0.214 ± 0.009
	$L/L_\odot$ ($T_{\rm eff}$, R)	19.7 ± 3.2
	M_V (g, $T_{\rm eff}$, M_*)	4.23 ± 0.13
	$E(B - V)$	0.128 ± 0.023
	d (V, M_V) (pc)	1190 ± 115

(1): from spectroscopy

(2): from asteroseismology

Excellent consistency with spectroscopic estimates, which was not guaranteed a priori!

Close to canonical value expected for sdBs

Rather thick envelope

4. Asteroseismic analysis

Comments on core and structural parameters

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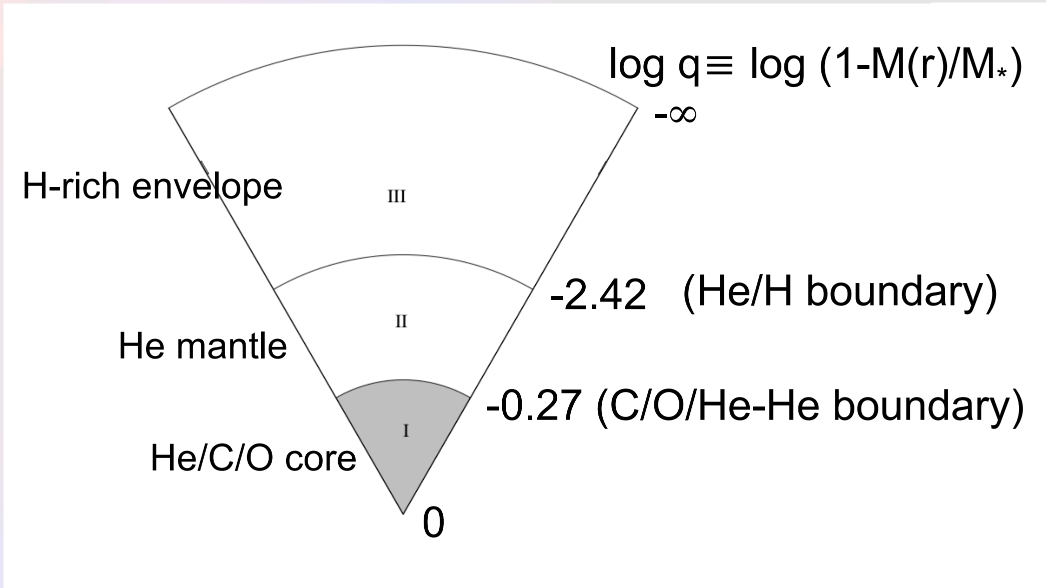
(1): from spectroscopy

(2): from asteroseismology

Thanks to g-modes, we can probe the core of sdBs from asteroseismology !

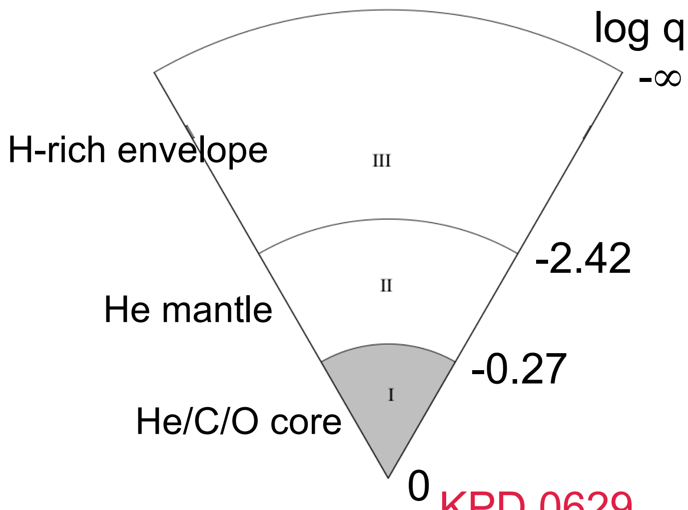


- Age of the sdB since ZAEHB, from comparison with evolutionary models: 42.6 Myr
- Size of convective core from Schwarzschild criterion (e.g. Dorman et al. 1993): log q ~ -0.20

Extension of (C+O) beyond the convective zone itself !

4. Asteroseismic analysis

Extension of the (C+O) beyond the convection zone: a common feature !



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

(2 possible solutions)

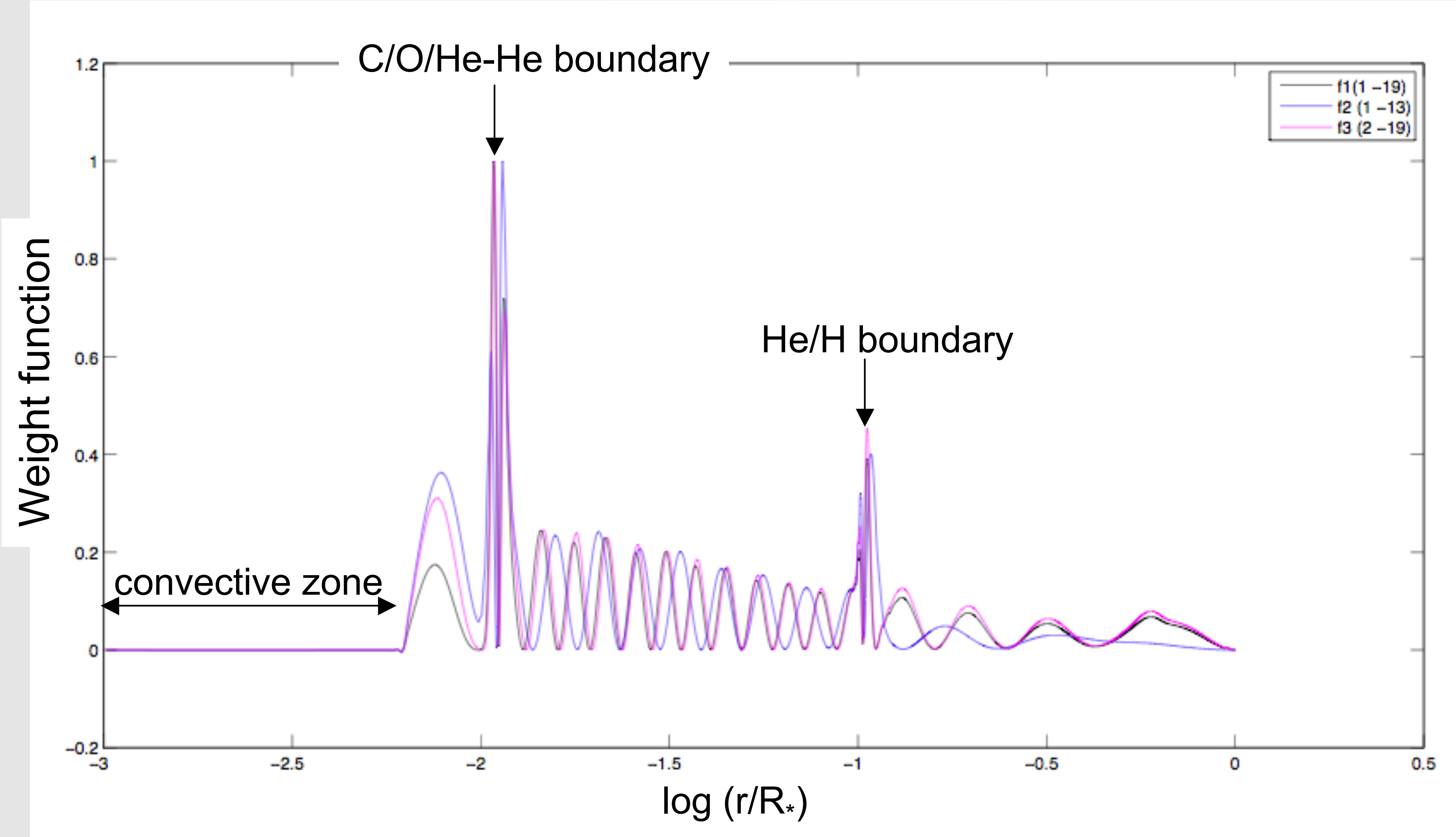
	KPD 0629 (59% He)	KPD 1943 (74% He)	KIC 0269 (82% He)	KIC 0269 (73% He)
	-2.42	-2.55	-2.30	-2.35
	-0.27	-0.37	-0.39	-0.30
Core extension:	0.11-0.14 R_*	0.116-0.175 R_*	0.105-0.165 R_*	0.11-0.15 R_*

- Size of convective core from Schwarzschild criterion (convection theory): between log q ~ -0.20 and -0.10: signature of transport of (C+O) beyond the convection zone itself
    - overshooting ?
    - and/or semi-convection ?
    - other? (differential rotation ?)

A way to constrain parameters of convection theories...

4. Asteroseismic analysis

Which pulsation modes are sensitive to the extension of the core ?



for KPD 0629: the dominant modes f_1, f_2, f_3 and f_5 are the most sensitive to the core (not a rule: different modes for different stars).

5. Conclusion and Prospects

Conclusion: Thanks to CoRoT (and *Kepler)*, we now have

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

Prospects:

- Already 15 of short- and long-period (and hybrid !) pulsating sdB stars discovered by *Kepler*, which are waiting for seismic modeling:
  - *Kepler* observations with -month and -year baseline
  - Study of core extensions
  - Determination of the rotation properties and core dynamics (single and binary stars)
  - Improve statistics (to date: 15 EHB stars modeled by seismology)