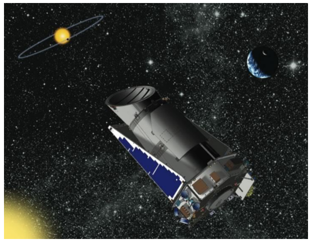
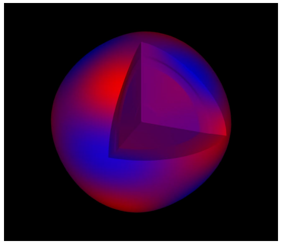


Les Houches February 2011

Topic of research : Astrophysics



Sounding the cores of stars by gravity-mode asteroseismology

Valerie Van Grootel

(Institut d'Astrophysique, University of Liege, Belgium)

Main collaborators

S. Charpinet (CNRS Toulouse)

G. Fontaine (U. Montreal)

S. Randall (ESO, Germany)

P. Brassard (U. Montreal)

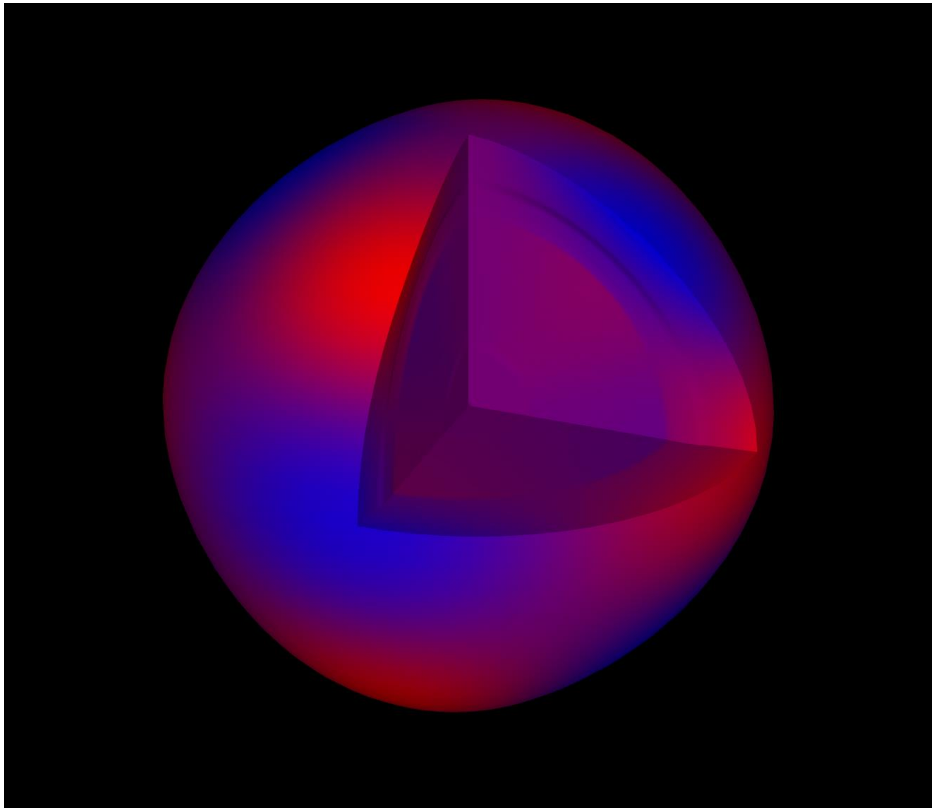
E.M. Green (U. Arizona, USA)

I. What is asteroseismology ?

What is asteroseismology ? ("stellar seismology")

Study the interiors of stars by the interpretation of their pulsation spectra

Goal : improve our knowledge of stellar interiors (stars are opaque...)



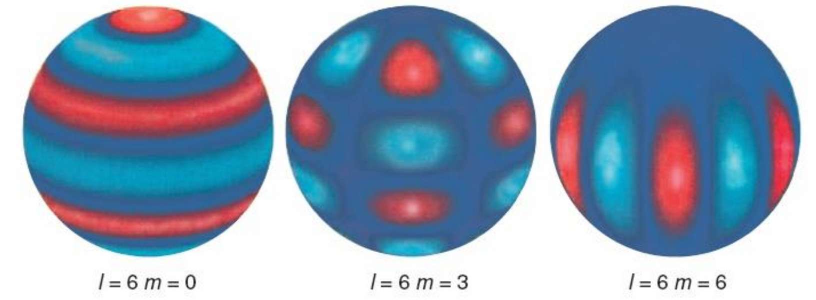
What is not well known ?

- Global properties (mass, structure)
- Convection properties (core, envelope)
- Thermonuclear fusion properties
- Microphysics (opacities)
- Microscopic transport (gravitational settling, radiative forces)
- Macroscopic transport (differential rotation,magnetism, etc.)
- ...

Theoretical grounds of asteroseismology

•From the linearized equations of hydrodynamics (small perturbations to equilibrium):

$$f'_{klm}(r,\theta,\phi,t) = f'_{kl}(r) Y_l^m(\theta,\phi) e^{i\sigma_{kl}t} \qquad (f' = p, v, T, ...)$$



- eigenfunction f'(r) (radial dependence)
- oscillation eigenfrequency σ_{kl} (temporal dep.)
- spherical harmonics Y_l^m (angular dep.)

•Lamb and Brunt-Väisälä frequency

$$L_l^2 = \frac{l(l+1)c_s^2}{r^2} \qquad\qquad N^2 = \frac{g^2\rho}{p}\frac{\chi_T}{\chi_\rho}(\nabla_{\rm ad} - \nabla + B)$$

Oscillations are excited and propagate in some regions, and are evanescent in others

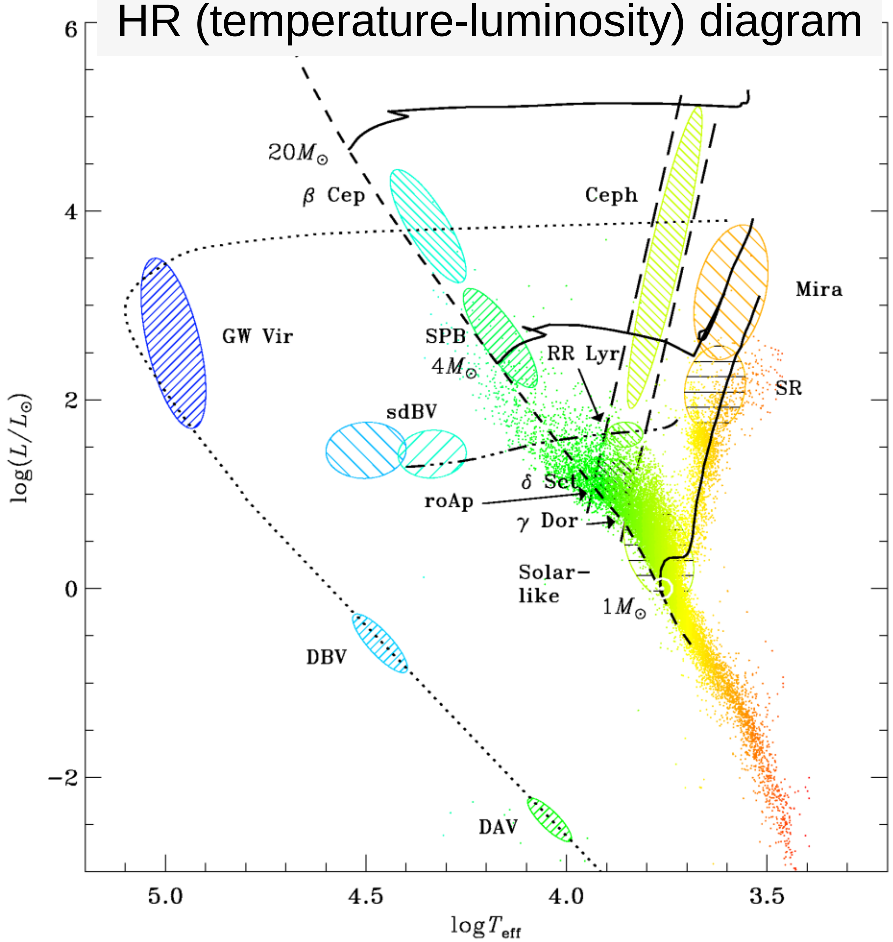
- if $\sigma^2 > L_l^2, N^2$: p-modes (restoring force : pressure), acoustic waves
- if $\sigma^2 < L_l^2, N^2$: g-modes (restoring force : buoyancy), gravity waves

Usually : p-modes sound the envelope, while g-modes propagate deep inside the stars

A zoo of pulsating stars

representative of different stages of evolution (from birth to "death")

HR (temperature-luminosity) diagram



<u>Main sequence stars</u>

(H-burning)

including the Sun

<u>Intermediate stages of evolution</u>

- Red Giants
- HB stars (He-burning)

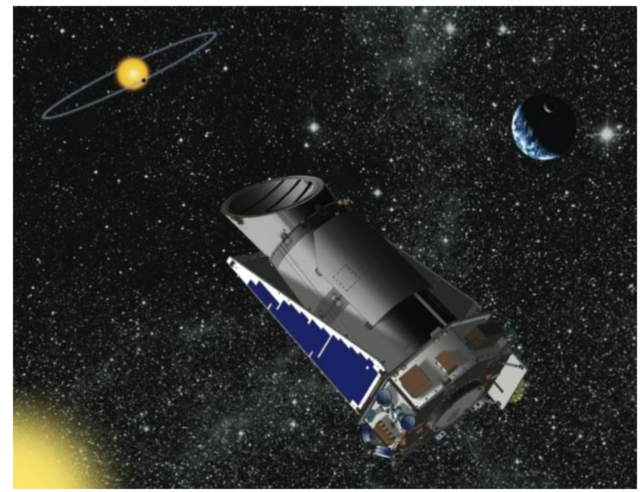
<u>Late stages of evolution</u>

White dwarfs (no burning)

p- and/or g-modes, periods from min to hours (and days), amplitudes less than 1%

A booming branch of astrophysics !

(*CO*nvection, *RO*tation, and Planetary *T*ransits)



- Launched 27th December, 2006
- CNES/ESA mission (FR/EU)
- Until mid-2013
- Next: PLATO ?

- Launched 7th March, 2009
- NASA mission (USA)
- Until 2015

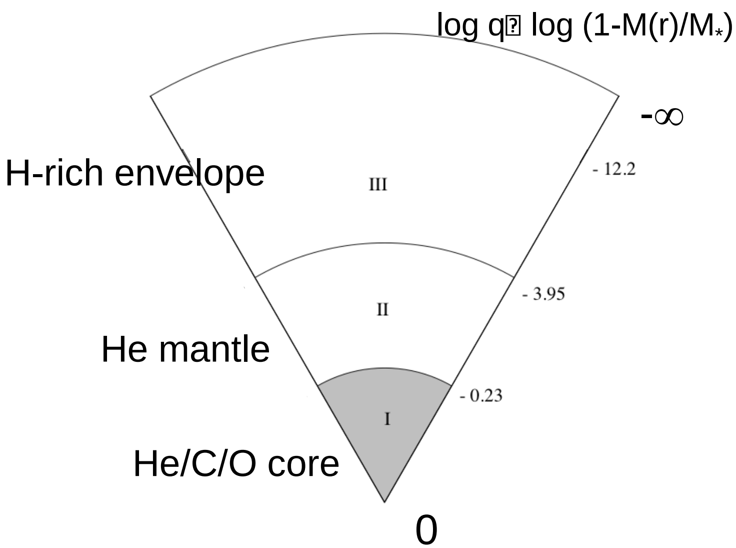
An illustrative example :
EHB stars Asteroseismology

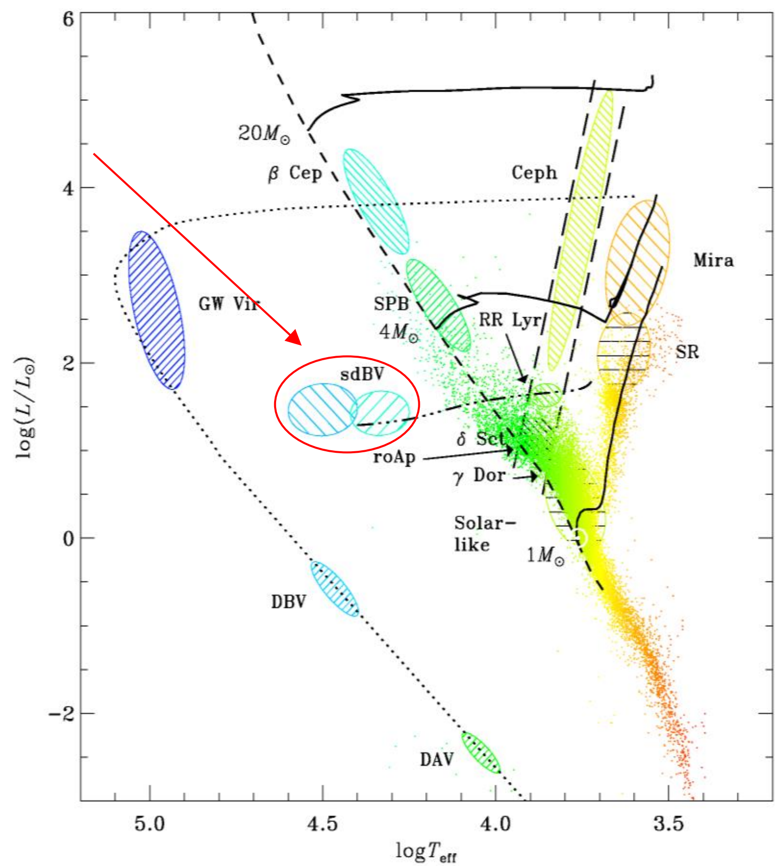
The Extreme Horizontal Branch (EHB) stars

Hot (T_{eff} ~ 30 000 K) and compact stars (log g ~ 5.5) belonging to Extreme Horizontal Branch (EHB), an intermediate stage of evolution

Internal structure:

I. He → C+O fusion (convective core)
II. radiative He mantle
III. radiative H-rich envelope
(M_{env} ~ 10^{-5} - 2.10^{-2} Msun pour M_* ~ 0.5 Msun)





Two cla… s:

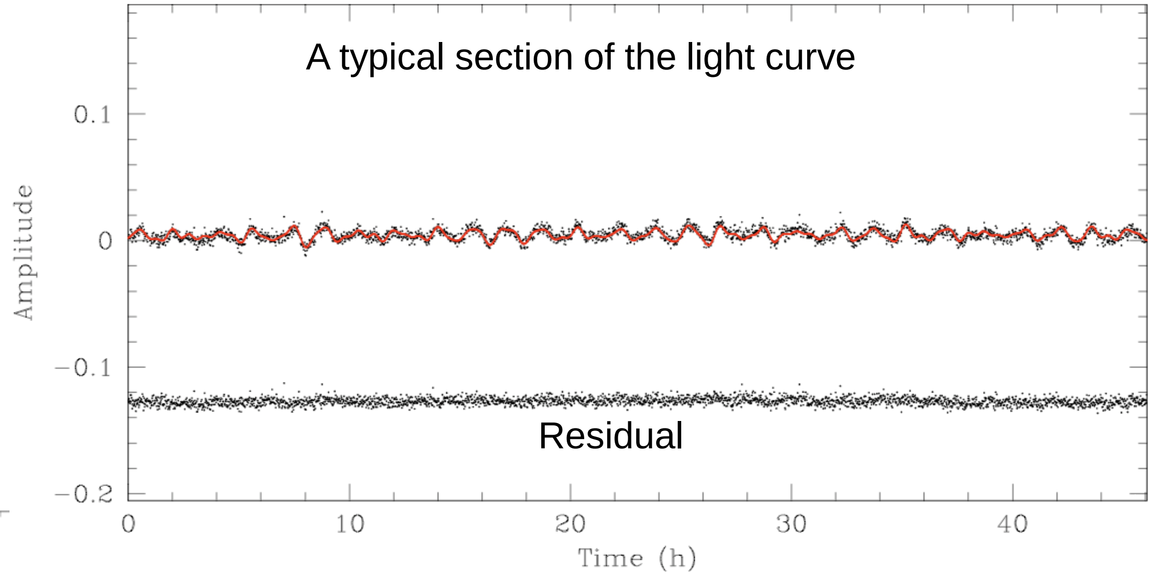
> short … les
(that so…

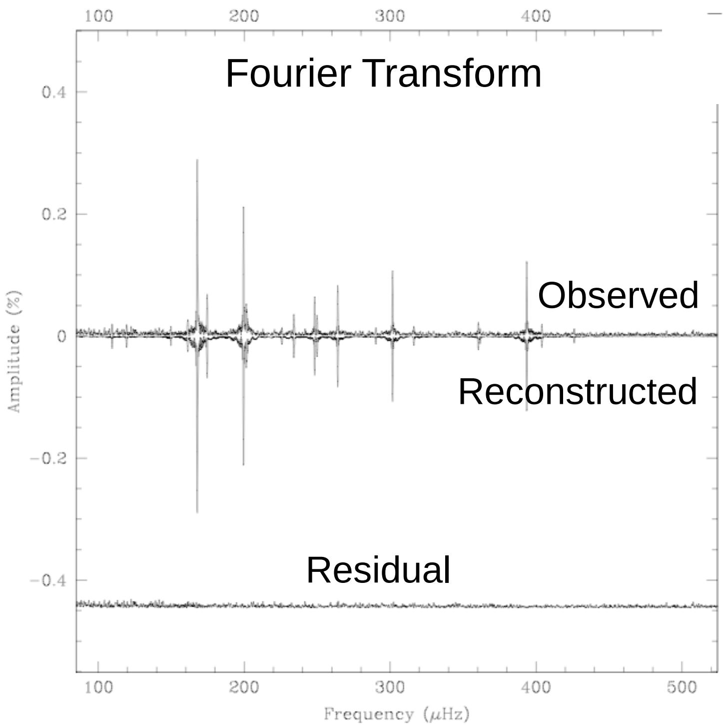
> long- … nodes
(that so… red !

NB: very slow rotating stars (months)

Kepler observations of the EHB star KPD 1943+4056

Observations in white light photometry





Frequencies extraction using prewithening techniques : 45 g-type periods

- in the range 2100 - 11200 s (~30 min to 3 h)
- with amplitudes between 0.12% and 0.004% (!)

Asteroseismic analysis : how does it work ?

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

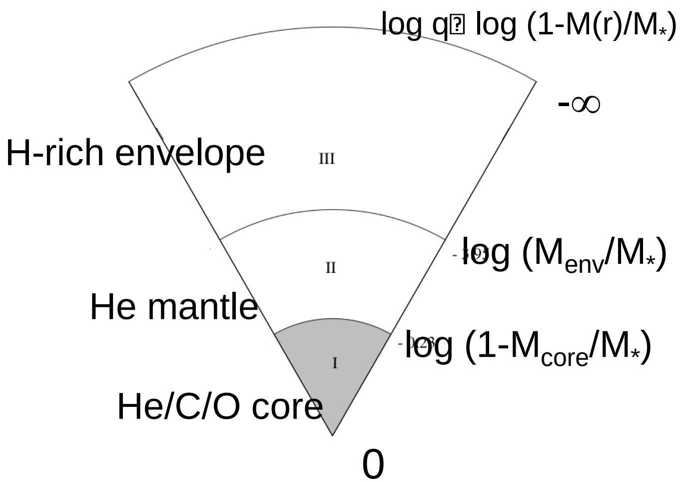
$$S^2 = \sum_{i=1}^{N_{\rm obs}} \left(P^i_{\rm obs} - P^i_{\rm th} \right)^2$$

- Model parameters : M_*, M_{env}, M_{core}, and core composition X(C+O)
- Efficient optimization codes (based on *Genetic Algorithms*) are used to find the minima of S^2, i.e. the potential asteroseismic solutions

> Optimization procedure hypotheses:

- Search parameter space:
  - $0.30 \leq M_*/M_{sun} \leq 0.70$
  - $-5.0 \leq \log (M_{env}/M_*) \leq -1.8$
  - $-0.40 \leq \log (1-M_{core}/M_*) \leq -0.10$
  - $0 \leq X(C+O) \leq 0.99$

Under the *external* constraints (3-σ uncertainties) from spectroscopy: $T_{eff} = 27\,730 \pm 810$ K and $\log g = 5.552 \pm 0.123$



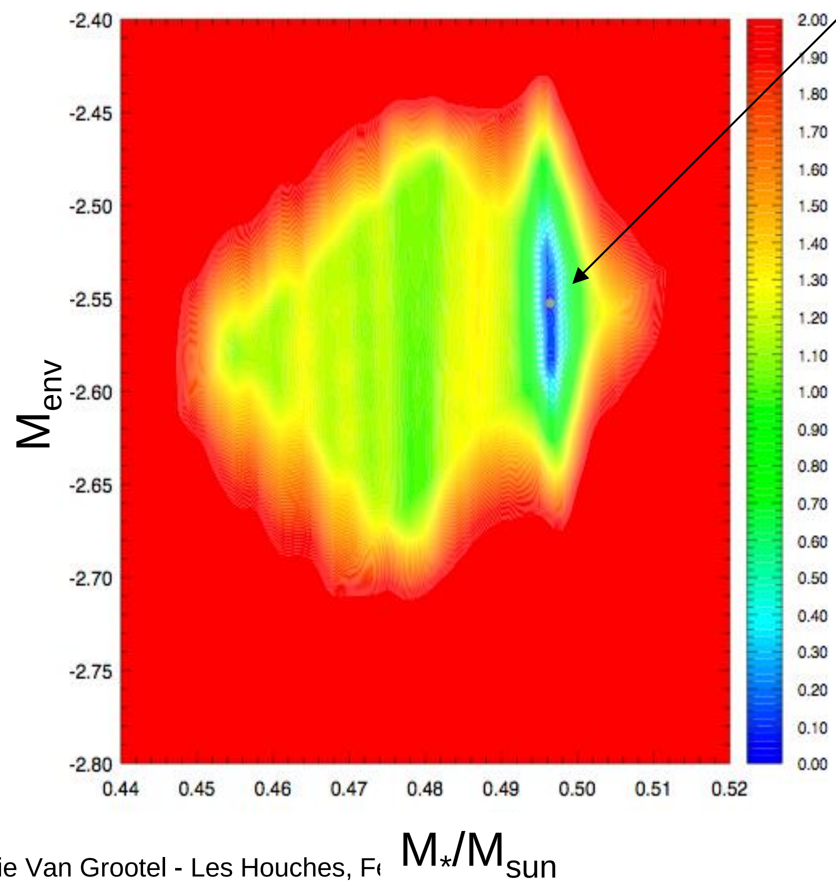
> Results: structural and core parameters of the star (M_*, M_{env},M_{core}, composition, etc.)

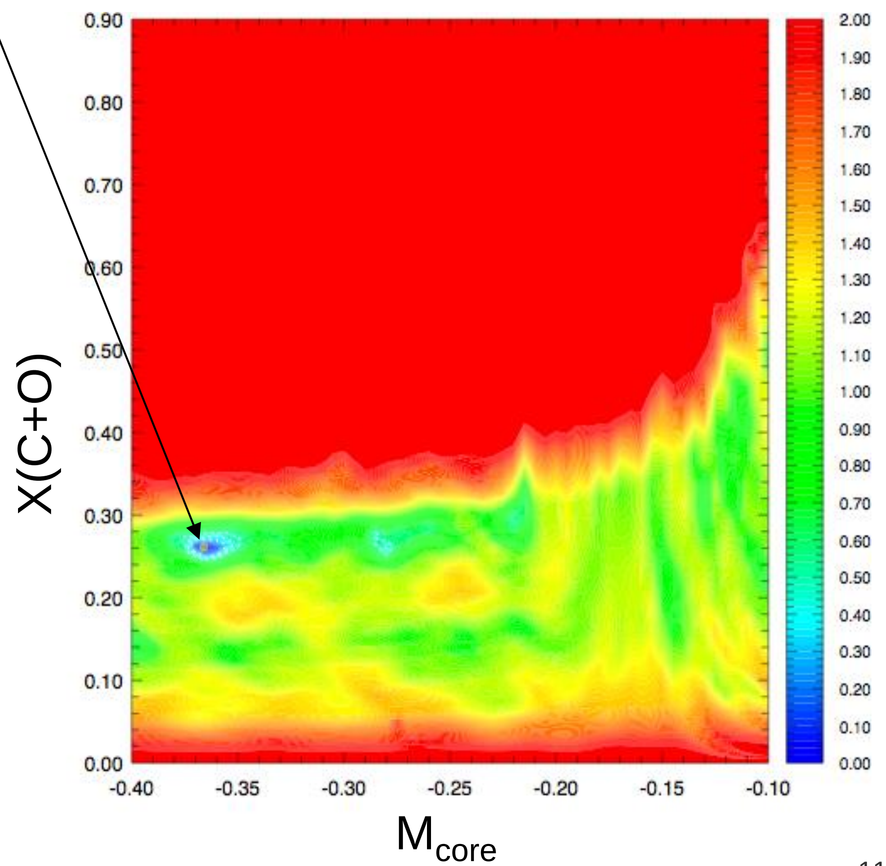
Asteroseismic analysis of KPD 1943+4058

A clear model comes out from the optimization procedure:

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

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





Asteroseismic analysis of KPD 1943+4058

Period fit and mode identification (extract)

Excellent fit to the 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	...	...	...	

Asteroseismic analysis of KPD 1943+4058

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

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

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

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

$R/R_\odot$, $L/L_\odot$ } Very little and luminous star

→ Power of asteroseismology !

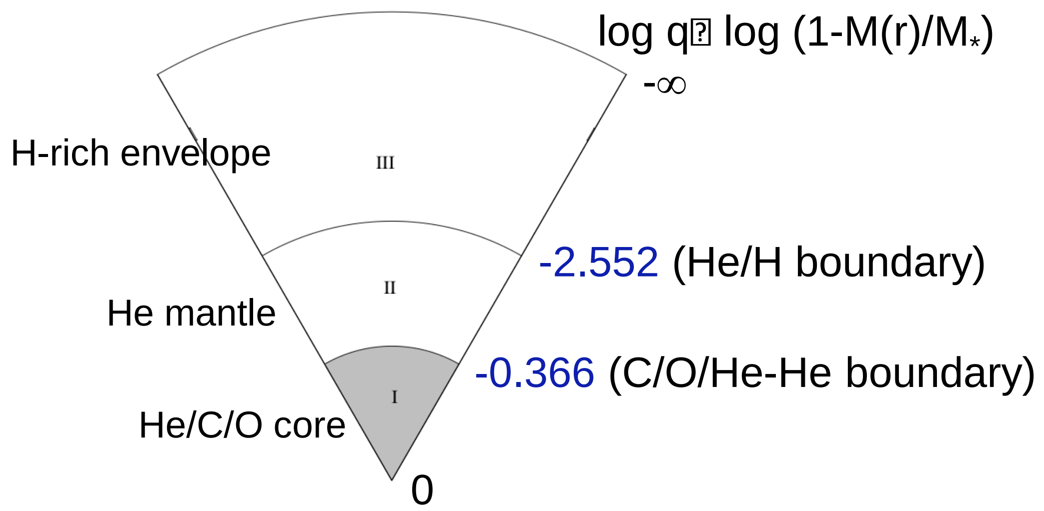
(a): from spectroscopy

(b): from asteroseismology

Asteroseismic analysis of KPD 1943+4058

Comments on core and structural parameters

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



- Size of convective core from Schwarzschild criterion (convection theory): log q ~ -0.20

→ 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...

Conclusion and Prospects

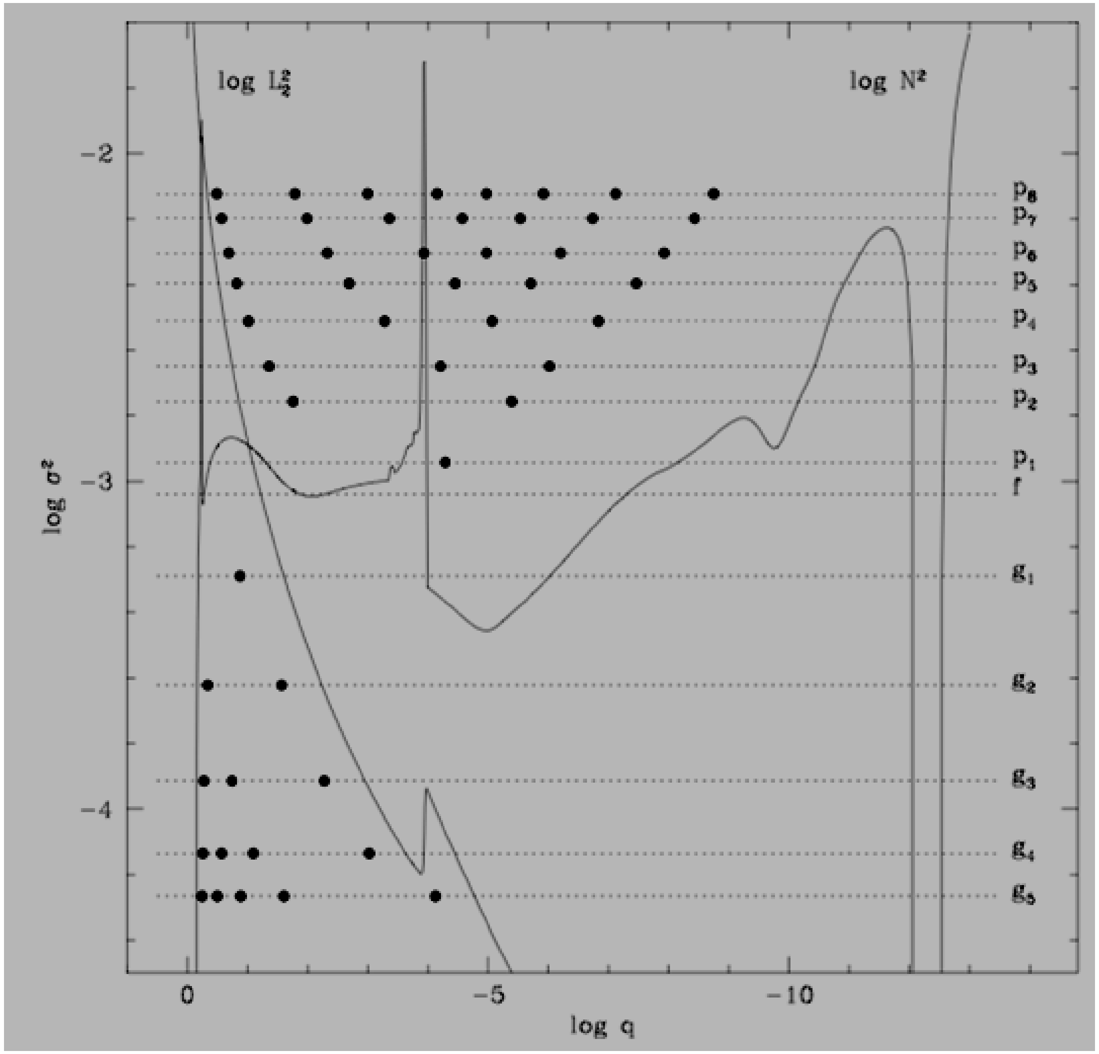
Conclusion: Thanks to g-mode seismology, we have access to

- Global parameters of the star (mass, radius, luminosity, etc.)
- Structural and core parameters (M_{env}, M_{core}, core composition, etc)
- Constraints for convection, stellar formation & evolution theories...

Prospects:

- Still tons of data from CoRoT and *Kepler,* which are waiting for seismic modeling…
  - *Kepler* observations with -month and -year baseline
  - Determination of the rotation properties and core dynamics (single and binary stars)
  - Improve statistics (to date: 14 EHB stars modeled by seismology)
- Currently also huge progress for other pulsating stars (solar-like pulsators, red giants)...

Brunt-Vaisala frequency profile



center surface

$$N^2 = \frac{g^2\rho}{p}\frac{\chi_T}{\chi_\rho}(\nabla_{\rm ad} - \nabla + B)$$