Progress in the front of Extreme Horizontal Branch star asteroseismology

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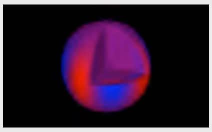
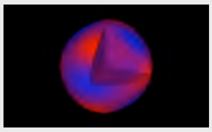


Abstract

We present basic principles, results and progress in the front of extreme horizontal branch stars (also known as "subdwarf B" or sdB stars) asteroseismology. The procedure developed to perform objective asteroseismic analysis of pulsating sdB stars is a "forward modeling" approach using efficient seismic diagnostic tools. The sdB stars are fairly hot and compact objects that correspond to an advanced stage of stellar evolution, after the main sequence and the first red giant branch. Asteroseismology of sdB stars is extremely fruitful to study several important aspects of stellar physics, as internal dynamics, angular momentum transport and convection properties. These also constitute the guidelines of the COROT mission, that will indeed observe the long-period sdB pulsator KPD 0629-0016 in last 2009.



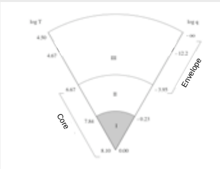
Introduction to subdwarf B (sdB) stars

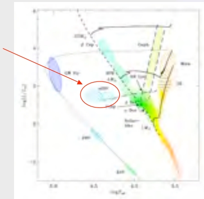
Hot (T_{eff} = 20 000 - 40 000 K) and compact (log g = 5.2 - 6.2) stars belonging to Extreme Horizontal Branch (EHB)

- Internal structure: convective He-burning core (I), radiative He mantle (II) and very thin H-rich envelope (III)
- Lifetime of ~ 10^8 yr on EHB, then evolve as low-mass white dwarfs
- At least 50% of sdB stars reside in binary systems, generally in close orbit (P_{orb} ≤ 10 days)

Two classes of multi-periodic sdB pulsators (sdBV)

> short-periods (P ~ 80 - 600 s), A ≤ 1%, mainly p-modes (shallow envelope modes)
> long-periods (P ~ 45 min - 2 h), A ≤ 0.1%, g-modes (internal modes, deep to convective core)





The forward modeling approach for asteroseismology (1)

Basic principle :

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

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

Step 1 : sdB internal structure calculation

> 2^{nd} generation models (Charpinet et al. 2002)

static structures with detailed description of mantle and envelope

- include non-uniform Fe profiles under radiative levitation in the envelope
- convective core considered as a "hard ball" (→ models suited for p-modes only)

Input parameters : T_{eff}, log *g*, envelope mass M_{env} and stellar mass M_*.

> 3^{rd} generation models (Brassard & Fontaine 2008, 2009, in prep.)

complete static structures (→ suited for p- and g-modes)

- built under the assumption of mechanical and thermal equilibrium
- core description including overshooting, nuclear burning and neutrinos effects

Input parameters : M_*, M_{env}, convective core mass M_{core} and composition (C, O & He abundances)

The forward modeling approach for asteroseismology (2)

Step 2 : Theoretical periods computation

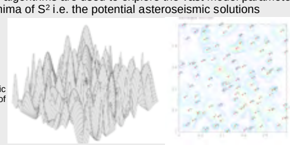
- Adiabatic & non-adiabatic theoretical periods computation (Brassard et al. 1992)
- The rotational multiplets (lifting (2*l*+1)-fold degeneracy) are calculated with the 1^{st} order perturbative approach :

$$\sigma_{klm} = \sigma_{kl} - m \int_0^R \Omega(r) K_{kl}(r) dr \quad ; \quad K_{kl}(r) = \frac{\xi_r^2 - [l(l+1)-1]\xi_h^2 - 2\xi_r\xi_h}{\int_0^R [\xi_r^2 + l(l+1)\xi_h^2] \rho r^2 dr} \rho r^2$$

Step 3 : Optimization procedure

- Efficient optimization 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

Capability of the optimization genetic algorithm to find all relevant optima of a complex function



Results

- Structural parameters of the star (T_{eff}, log g , M_*, envelope thickness, possibly size & composition of the core, etc.)
- Identification (*k*,*l*,*m*) of the pulsation modes (within or not external constraints)
- Internal dynamics Ω(r)

An illustrative asteroseismic analysis
The example of PG 1336-018 (NY Virginis)

The close eclipsing binary system PG 1336-018

pulsating sdB star + secondary dwarf M
P_{orb} = 8 728 s (Kilkenny et al. 2000)

Unique sdB pulsator in an eclipsing system

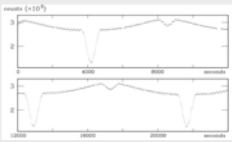


Figure from Kilkenny et al. (2003)

- 25 pulsation periods in the range 96 – 205 s exhibited by the sdB component (Kilkenny et al. 2003), including rotational splitting providing information on internal dynamics
- Orbital motion modelization (Vuckovic et al. 2007):
  → 3 solutions (e.g. for sdB mass and radius) of equal probability

⇓

Unique possibility to compare with sdB mass and radius found by asteroseismology

- Atmospheric parameters from spectroscopy (weigthed mean values from low-resolution spectra):
  - T_{eff} = 32 780 ± 200 K
  - log g = 5.76 ± 0.04
  - log N(He)/N(H) = –2.94 ± 0.14

Asteroseismic analysis with the forward modeling approach

Asteroseismic analysis using 2^{nd} *generation* sdB models (Charpinet et al. 2008)

> Determination of the structural parameters of the sdB star, with $\overline{\Delta P/P}$ ~ 0.17%

	Seismic model	Orbital solutions (Vuckovic et al. 2007)		
T_{eff} (K)	32 740 ± 400	—	—	—
log *g*	5.739 ± 0.002	5.74 ± 0.05	5.77 ± 0.06	5.79 ± 0.07
$M_*/M_\odot$	0.459 ± 0.005	0.389 ± 0.005	0.466 ± 0.006	0.530 ± 0.007
$\log(M_{env}/M_*)$	−4.54 ± 0.07	—	—	—
$R_*/R_\odot$ (M_*, *g*)	0.151 ± 0.001	0.14 ± 0.01	0.15 ± 0.01	0.15 ± 0.01
$L_*/L_\odot$ (T_{eff}, *R*)	23.3 ± 1.5	—	—	—
M_V (*g*, T_{eff}, M_*)	4.49 ± 0.04	—	—	—
d (*V*, M_V) (pc)	619 ± 38	—	—	—
log N(He)/N(H)	—	—	—	—
P_{rot} (h)†	2.42438	—	—	—
V_{eq} (P_{rot}, *R*) (km/s)	75.9 ± 0.6*	—	—	—

Very first attempt of seismic analysis using 3^{rd} generation models :

> essentially same structural parameters are found ($\overline{\Delta P/P}$ ~ 0.16%)

- M_* = 0.472 M_s
- $\log(M_{env}/M_*)$ = –3.83
- $\log(M_{core}/M_*)$ = –0.297
- core composition : 43% C, 12% O and 45% He

⇒ T_{eff} = 32 733 K, log g = 5.775

These are very preliminary results. The errors are still to be calculated, particularly concerning details of the convective core (real sensitivity of p-modes to them ?)

Rotation properties by asteroseismology

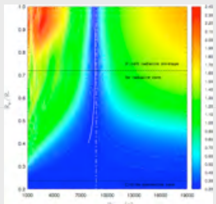
Is the sdB component synchronized (P_{rot} = P_{orb})?

> Synchronization times (e.g. Zahn 1975; Tassoul & Tassoul 1992) depend notably on the orbital period and the age of the component, which cannot directly be inferred from our static models

> Strategy : we investigate the rotation of two arbitrary layers in the star (differential rotation). Transition vary from 0.1 to 1.0 R_*. Structural parameters and surface rotation fixed (to 8728 s). Optimization on core rotation period P_{core}

sdB PG 1336-018 is tidally locked from surface to ~ 0.55 R_* at least

(dynamics of deeper regions cannot be inferred from the p-modes involved here)



This result gives new constraints to angular momentum transport theories

The future of sdB stars asteroseismology

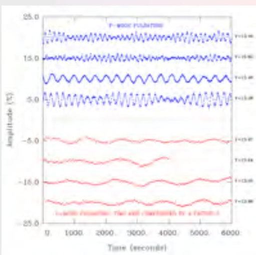
Seismology of long-period pulsating sdB stars

- To date, 10 "short-period" sdB pulsators have been scrutinized by asteroseismology
- The availability of 3^{rd} generation models opens now the opportunity to carry out "long-period" sdB pulsators (exhibiting g-modes) full seismic analysis

- Sensitivity of g-modes to much deeper regions allows
  - Accurate determination of convective core details (composition, size, overshooting region)
  - Knowledge of dynamical behavior in deep regions, in order to complete internal rotation profiles as a function of depth

→ High complementarity between the two sdB pulsators classes

- Amplitudes generally less than 0.1% and fairly long (~1h) periods
  → continuous high-sensitivity and long-time baseline observations (e.g. from space) are needed



COROT observation of the long-period sdB pulsator KPD 0629-0016

(Short Run Anticentre No 3 - PI S. Charpinet)

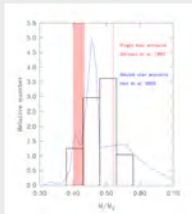
All data analysis procedures, models and seismic diagnostic tools are now ready

Main objectives

> Testing the sdB formation scenarios

Single and binary evolution scenarios (Dorman et al. 1993, Han et al. 2003) for the sdB stars formation leave clear distinct imprints on structural sdB parameters, e.g. total mass

→ comparison with asteroseismic total mass distribution, to better constrain stellar evolution theories. A representative sample (at a statistical point of view) is needed for that purpose.



> Rotation properties by asteroseismology

- For sdB components in binary systems :
  New constraints for tidal dissipation theories and angular momentum transport
- For single sdB stars :
  Angular momentum evolution since main sequence and first giant branch

> Convection properties by asteroseismology

- Determination of the size of the convective core, including the extension of the overshooting region
- Determination of the core composition (He/C/O mixture)
- By comparison with evolutionary models (Dorman 1992), evaluation of the age of the sdB star

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