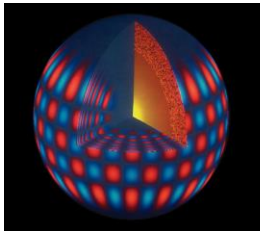
The fourth meeting on hot subdwarf stars
and related objects



Progress in the asteroseismic analysis of the pulsating sdB star PG 1605+072

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Outline

1. Introduction to the pulsating sdB star PG 1605+072
    - Photometric observations
    - Spectroscopic observations
    - Is PG 1605+072 a fast rotator ?
2. Models and Method for the asteroseismic analysis
3. Asteroseismic analysis : hypothesis of a slow rotation
4. Asteroseismic analysis : hypothesis of a fast rotation
5. Comparison between the two hypotheses
6. Conclusion and raising questions

1. Introduction to PG 1605+072

"PG 1605+072, a unique pulsating sdB star"

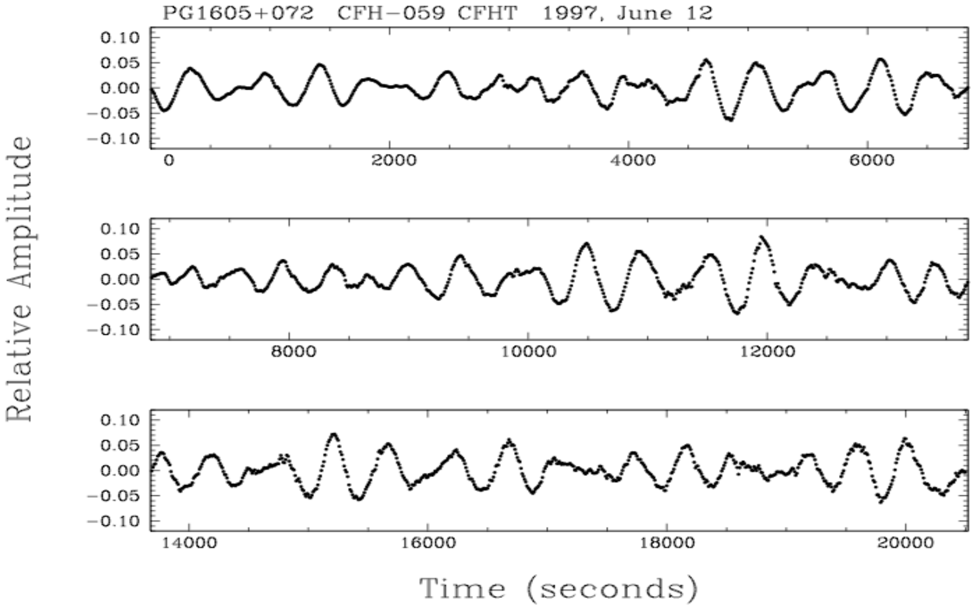
> Koen et al. (1998a) : discovery of a rapidly pulsating sdB star (EC14026 class) with an unusually rich pulsation spectrum and long periods (200 - 600 s)

> Kilkenny et al. (1999), multi-site campaign (180h data over 15 days - 1μHz resolution) : 44 pulsation periods useful for asteroseismology (28 totally reliable)

> van Spaandonk et al. (2008), from 4-days campaign @ CFHT (~ 4μHz resolution) : 46 pulsation periods useful for asteroseismology, including 38 common with Kilkenny

Light curve particularities

- no real sinusoidal form
- no clear pseudo-period
- very high amplitudes for dominant modes :
  - f_1 : A=64 mmags (~2.5%)
  - f_2 to f_5 : A $\geq$ 1%
- no sign of companion



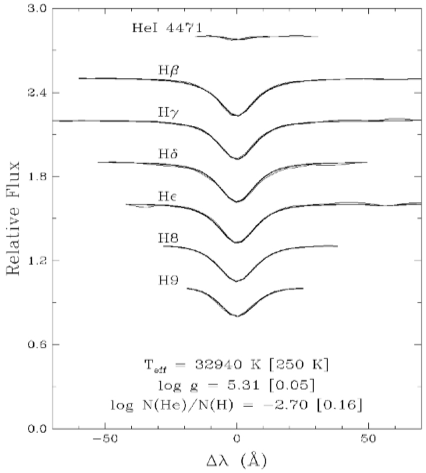
1. Introduction to PG 1605+072

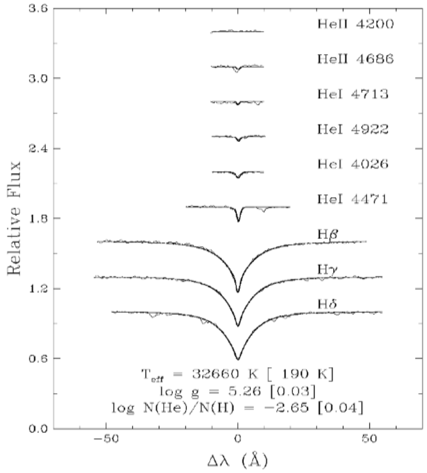
Spectroscopic observations : atmospheric parameters

- Heber et al. (1999), Keck-HIRES (0.1Å), averaged LTE with metals and NLTE models:
  - $T_{\rm eff} = 32\,300 \pm 300$ K
  - $\log g = 5.25 \pm 0.1$

- G. Fontaine, 2.3-m Kitt Peak (9Å), NLTE:
  - $T_{\rm eff} = 32\,940 \pm 450$ K
  - $\log g = 5.31 \pm 0.08$

- G. Fontaine, 6-m MMT (1Å), NLTE:
  - $T_{\rm eff} = 32\,660 \pm 390$ K
  - $\log g = 5.26 \pm 0.05$





Averaged mean value : $T_{\rm eff} = 32\,630 \pm 600$ K and $\log g = 5.273 \pm 0.07$

Very low surface gravity for an EC14026 star → Evolved state beyond TA-EHB ?

Very low surface gravity for an EC14026 star → Very high-mass sdB star ?

1. Introduction to PG 1605+072

Is PG 1605+072 a fast rotator ?

> Line broadening

measured by Heber et al. (1999) :

39 km s^{-1}

(unusually high for a sdB star)

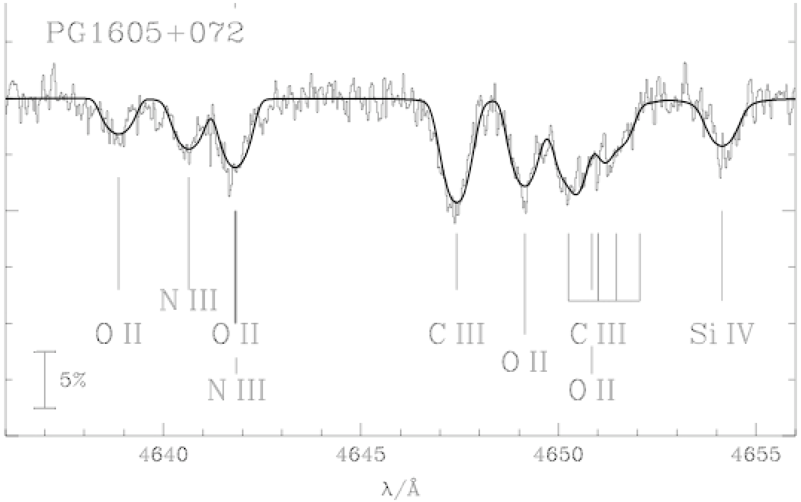


Figure from Heber et al. (1999)

> Rotational broadening ? $\Rightarrow V_{eq} \sin i = 39$ km s^{-1}

- PG 1605+072 is a fast rotator, as suggested by Kawaler (1999). This explains the complexity of the pulsation spectrum, by the lift of (2l+1)-fold degeneracy in frequencies

> Pulsational broadening ?

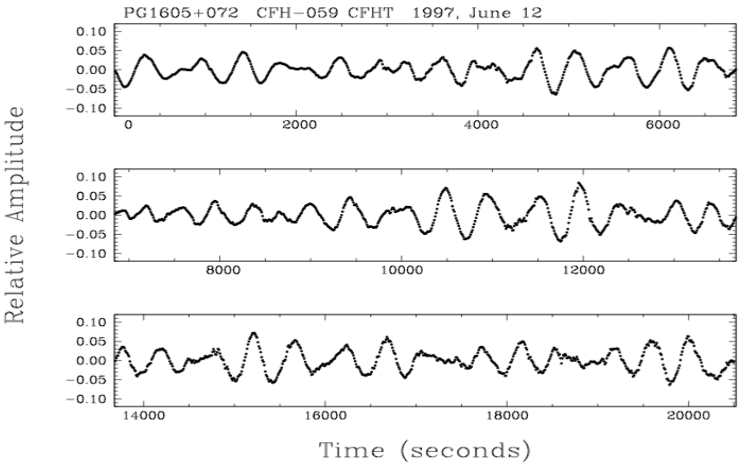
- Kuassivi et al. (2005), FUSE spectra : Doppler shift of 17 km s^{-1}
- O'Toole et al. (2005), MSST : 20 pulsation modes by RV method, amplitudes between 0.8 and 15.4 km s^{-1}

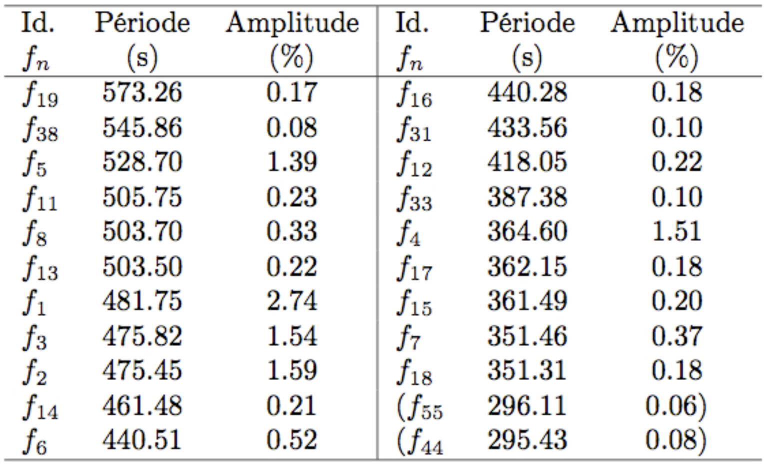
$\Rightarrow V_{eq} \sin i \ll 39$ km s^{-1} $\Rightarrow$ origin of the complexity of the pulsation spectrum ?

1. Introduction to PG 1605+072

Suggestion from P. Brassard :

Lots of low-amplitude pulsation frequencies are due to 2^{nd}- and 3^{rd}-order harmonics and nonlinear combinations of high amplitude frequencies.





Id. f_n	Période (s)	Amplitude (%)	Id. f_n	Période (s)	Amplitude (%)
f_{19}	573.26	0.17	f_{16}	440.28	0.18
f_{38}	545.86	0.08	f_{31}	433.56	0.10
f_5	528.70	1.39	f_{12}	418.05	0.22
f_{11}	505.75	0.23	f_{33}	387.38	0.10
f_8	503.70	0.33	f_4	364.60	1.51
f_{13}	503.50	0.22	f_{17}	362.15	0.18
f_1	481.75	2.74	f_{15}	361.49	0.20
f_3	475.82	1.54	f_7	351.46	0.37
f_2	475.45	1.59	f_{18}	351.31	0.18
f_{14}	461.48	0.21	(f_{55}	296.11	0.06)
f_6	440.51	0.52	(f_{44}	295.43	0.08)

- All the pulsation spectrum can be reconstructed from 22 basic frequencies, including the highest amplitude ones
- Some of these can be interpreted as very close frequency multiplets (slow rotation)

⇒14 independent pulsation modes remain to test the idea of a slow rotation for PG 1605+072, in a seismic analysis by comparison with $\sigma_{kl,m=0}$ theoretical frequencies

2. Models and Method for asteroseismology

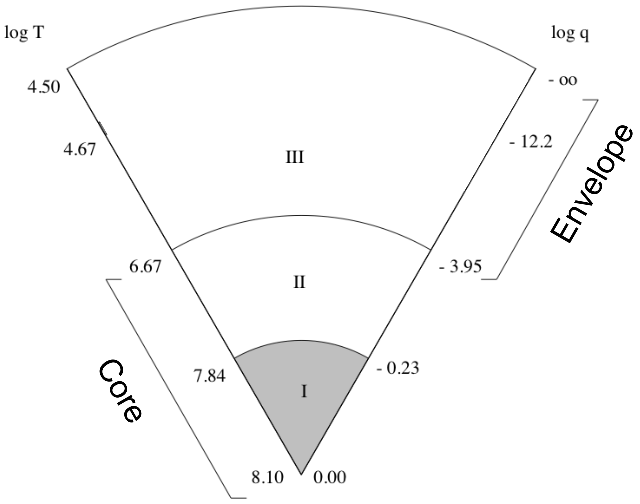
> 2^{nd} generation models

- static envelope structures; central regions (e.g. convective core) ≡ hard ball
- include detailed envelope microscopic diffusion (nonuniform envelope Fe abundance)
- 4 input parameters : T_{eff}, log g, M_*, envelope thickness $\log (M_{env}/M_*)$

> 3^{rd} generation models

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

With 3^{rd} generation models,
T_{eff} and log g are computed a posteriori
⇒
Atmospheric parameters from spectroscopy are used as external constraints for seismic analysis



2. Models and Method for asteroseismology

The forward modeling approach for asteroseismology

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

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

- The rotational multiplets (lifting (2*l*+1)-fold degeneracy) are calculated by 1st order perturbative approach :

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

- Efficient optimization 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

Results :

- Structural parameters of the star ($T_{\rm eff}$, log g, M_*, envelope thickness, etc.)
- Identification (*k*,*l*,*m*) of pulsation modes (with or without external constraints)
- Internal dynamics Ω(r)

3. Asteroseismic analysis : Hypothesis of a slow rotation

Search the model whose $\sigma_{kl,m=0}$ theoretical frequencies best fit the 14 observed ones

(other frequencies can be interpreted as very close frequency multiplets, or harmonics, or nonlinear combinations)

Hypotheses :

> Search parameter space :

- $0.30 \leq M_*/M_s \leq 1.10$ (Han et al. 2002, 2003)
- $-6.0 \leq \log (M_{env}/M_*) \leq -1.8$
- $-0.40 \leq \log (M_{core}/M_*) \leq -0.02$
- $0 \leq X(C+O) \leq 1$

Under the constraints $T_{eff} = 32\,630 \pm 600$ K and $\log g = 5.273 \pm 0.07$

> Forbid $l=3$ associations for visibility reasons (Randall et al. 2005)

Best-fit model by optimization procedure :

- $M_* = 0.7624\ M_s$
- $\log (M_{env}/M_*) = -2.6362$
- $\log (M_{core}/M_*) = -0.0240$
- $X(C+O) = 0.45$; $X(He) = 0.65$

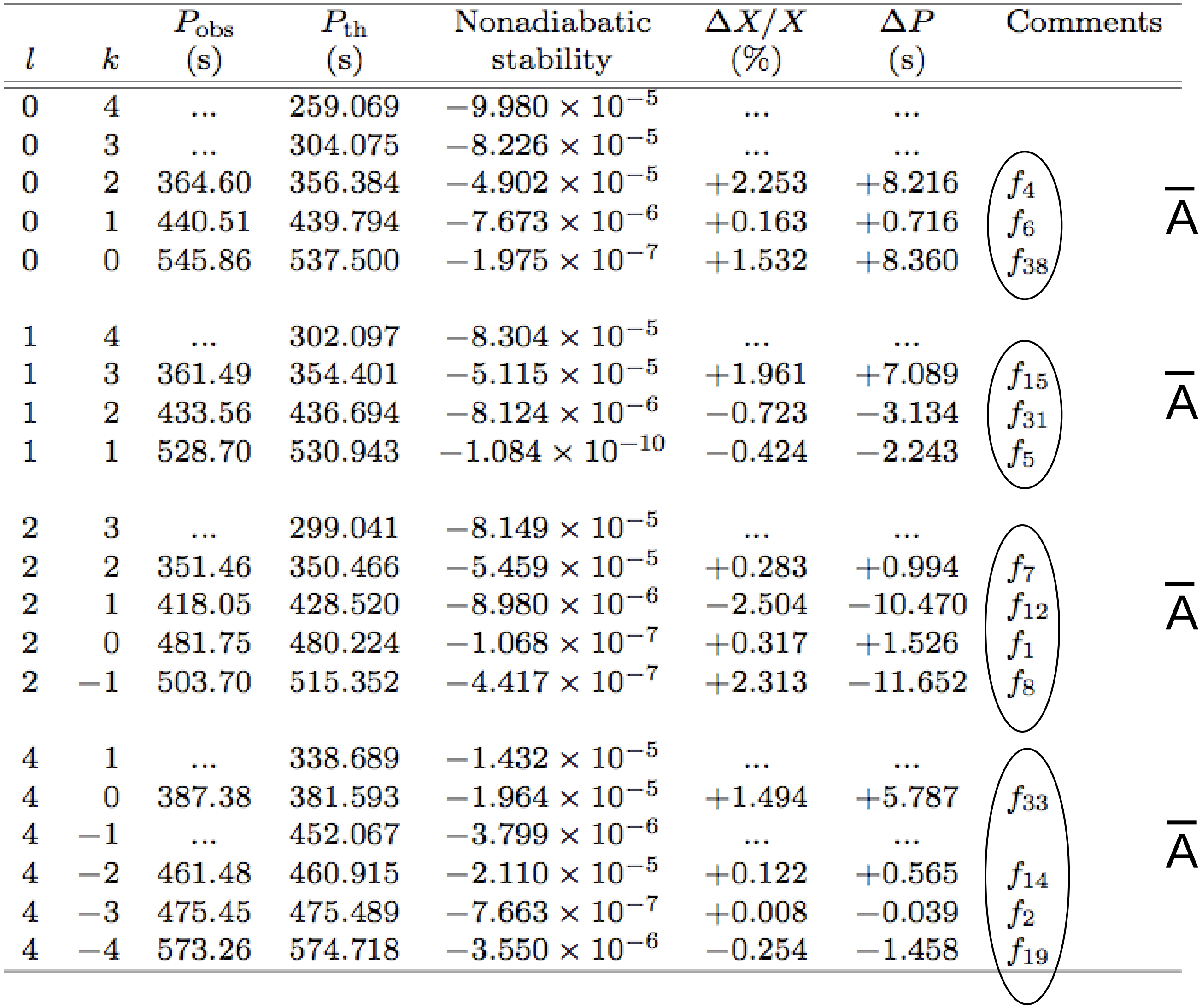
$\Rightarrow$ $T_{eff} = 32\,555$ K

$\log g = 5.2906$

Period fit : $S^2 \sim 3.71 \Leftrightarrow \overline{\Delta P/P} \sim 1.03\%$ or $\overline{\Delta P} \sim 4.45$ s (relatively good fit)

3. Asteroseismic analysis : Hypothesis of a slow rotation

Period fit and mode identification



l	k	$P_{\rm obs}$ (s)	$P_{\rm th}$ (s)	Nonadiabatic stability	$\Delta X/X$ (%)	ΔP (s)	Comments
0	4	...	259.069	-9.980×10^{-5}	...	...	
0	3	...	304.075	-8.226×10^{-5}	...	...	
0	2	364.60	356.384	-4.902×10^{-5}	+2.253	+8.216	f_4
0	1	440.51	439.794	-7.673×10^{-6}	+0.163	+0.716	f_6
0	0	545.86	537.500	-1.975×10^{-7}	+1.532	+8.360	f_{38}
1	4	...	302.097	-8.304×10^{-5}	...	...	
1	3	361.49	354.401	-5.115×10^{-5}	+1.961	+7.089	f_{15}
1	2	433.56	436.694	-8.124×10^{-6}	−0.723	−3.134	f_{31}
1	1	528.70	530.943	-1.084×10^{-10}	−0.424	−2.243	f_5
2	3	...	299.041	-8.149×10^{-5}	...	...	
2	2	351.46	350.466	-5.459×10^{-5}	+0.283	+0.994	f_7
2	1	418.05	428.520	-8.980×10^{-6}	−2.504	−10.470	f_{12}
2	0	481.75	480.224	-1.068×10^{-7}	+0.317	+1.526	f_1
2	−1	503.70	515.352	-4.417×10^{-7}	+2.313	−11.652	f_8
4	1	...	338.689	-1.432×10^{-5}	...	...	
4	0	387.38	381.593	-1.964×10^{-5}	+1.494	+5.787	f_{33}
4	−1	...	452.067	-3.799×10^{-6}	...	...	
4	−2	461.48	460.915	-2.110×10^{-5}	+0.122	+0.565	f_{14}
4	−3	475.45	475.489	-7.663×10^{-7}	+0.008	−0.039	f_2
4	−4	573.26	574.718	-3.550×10^{-6}	−0.254	−1.458	f_{19}

$\bar{A}$ ~ 0.70 %

$\bar{A}$ ~ 0.56%

$\bar{A}$ ~ 0.91%

$\bar{A}$ ~ 0.51%

3. Asteroseismic analysis : Hypothesis of a slow rotation

Comments on structural parameters

> on X(C+O) and log (M_{core}/M_*)

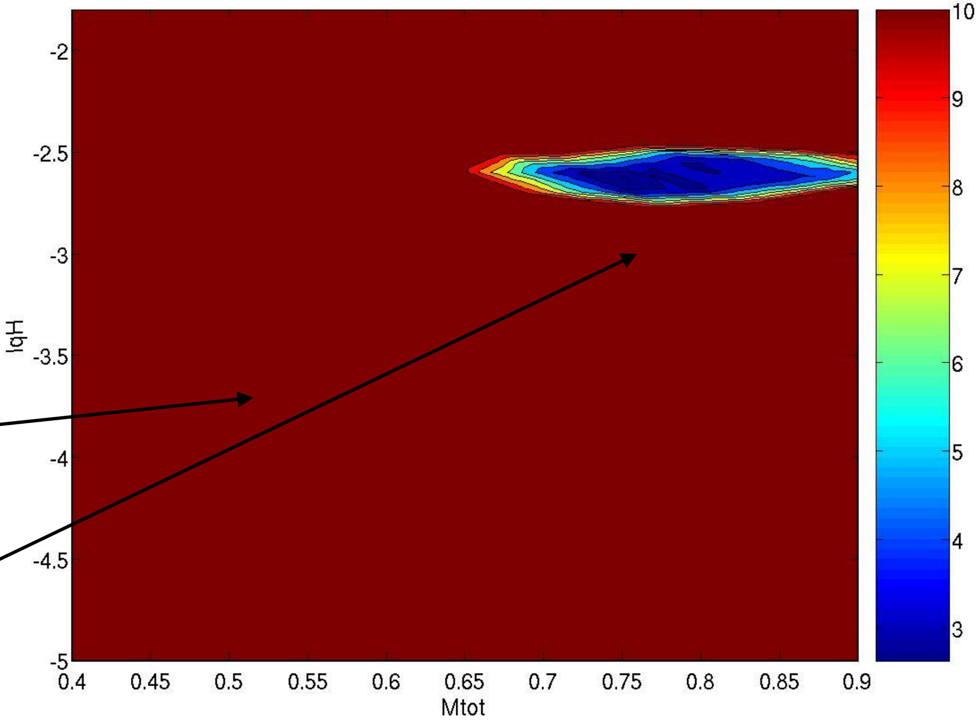
not consistent with external
spectroscopic constraints

> on M_* and log (M_{env}/M_*)

M_{core} and X(C+O) are interdependant
and not well defined (lack of sensitivit
of pulsation modes to central regions

not consistent with external
spectroscopic constraints

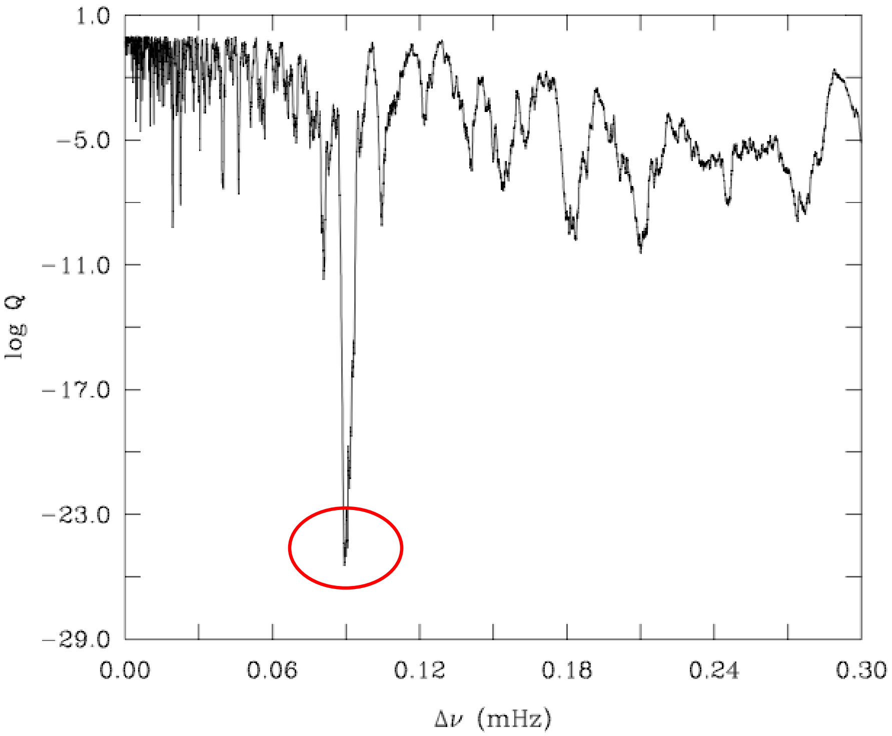
quite well defined by pulsation
spectrum and external spectroscopic
constraints



We *find* a very-high mass and thick envelope model on EHB for PG 1605+072, consistent with the hypothesis of a slow rotation

4. Asteroseismic analysis : Hypothesis of a fast rotation

Search the model whose σ_{klm} theoretical frequencies best fit the 28 “totally reliable” observed ones (Kilkenny et al. 1999)



Kolmogorov-Smirnov test

(gives the credibility of regular spacings in pulsation spectrum)

$$\Delta\nu \sim 90.4\ \mu\text{Hz}$$

$$\Leftrightarrow$$

$$P_{rot} \sim 11\,000\ \text{s}\ (\sim 3\ \text{h})$$

Remark : our 1st order perturbative approach for rotation is valid up to ≥ 2.5h (Charpinet et al. 2008)

4. Asteroseismic analysis : Hypothesis of a fast rotation

\> Search parameter space :

- $0.30 \leq M_*/M_s \leq 1.10$ (Han et al. 2002, 2003)
- $-6.0 \leq \log (M_{env}/M_*) \leq -1.8$
- $-0.40 \leq \log (M_{core}/M_*) \leq -0.02$
- $0 \leq X(C+O) \leq 1$
- solid rotation : $8000\ \mathrm{s} \leq P_{rot} \leq 16000\mathrm{s}$

Under the constraints $T_{eff} = 32\,630 \pm 600$ K and $\log g = 5.273 \pm 0.07$

\> Forbid $l=3$ associations for visibility reasons (Randall et al. 2005)

Best-fit model by optimization procedure :

- $M_* = 0.7686\ M_s$
- $\log (M_{env}/M_*) = -2.7114$
- $\log (M_{core}/M_*) = -0.0722$
- $X(C+O) = 0.28$; $X(He) = 0.72$
- $P_{rot} = 11\,075\ \mathrm{s} = 3.076\ \mathrm{h}$

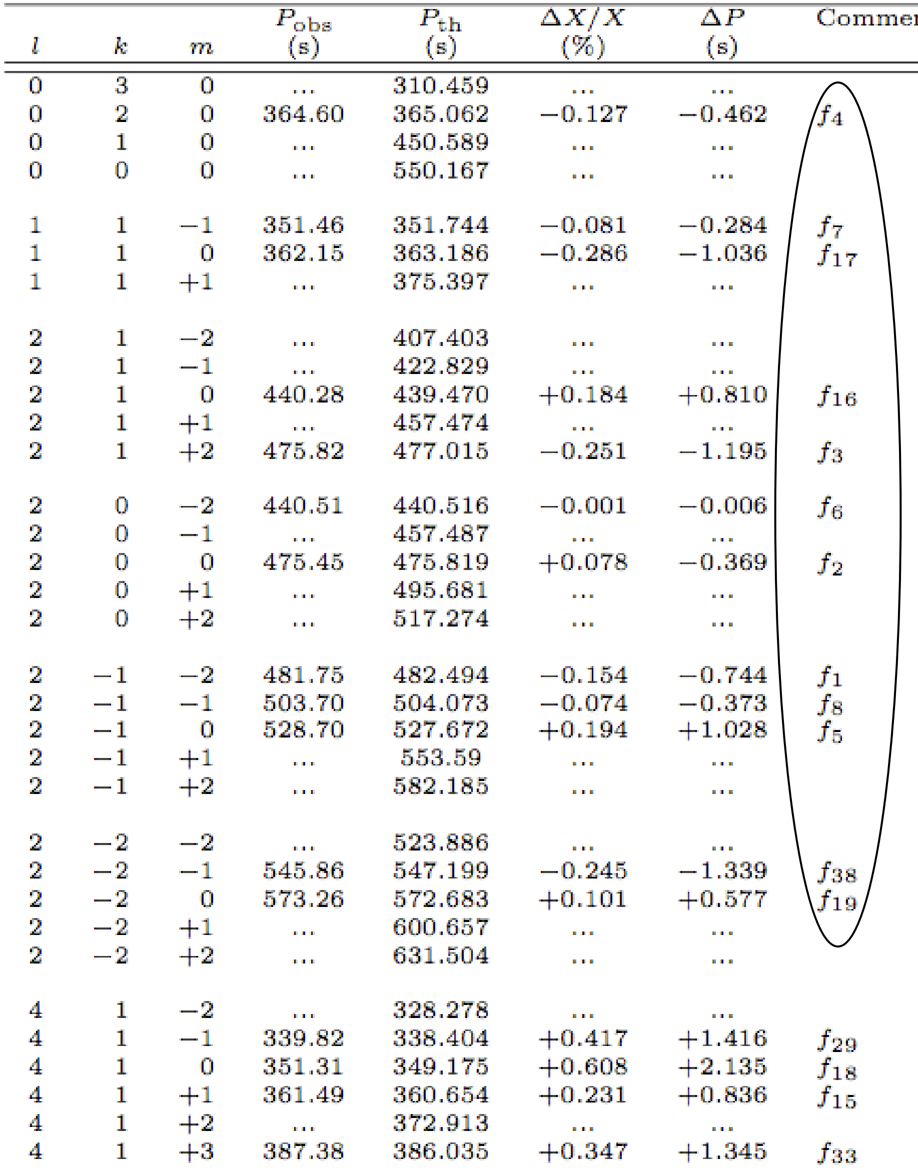
$T_{eff} = 32\,723$ K

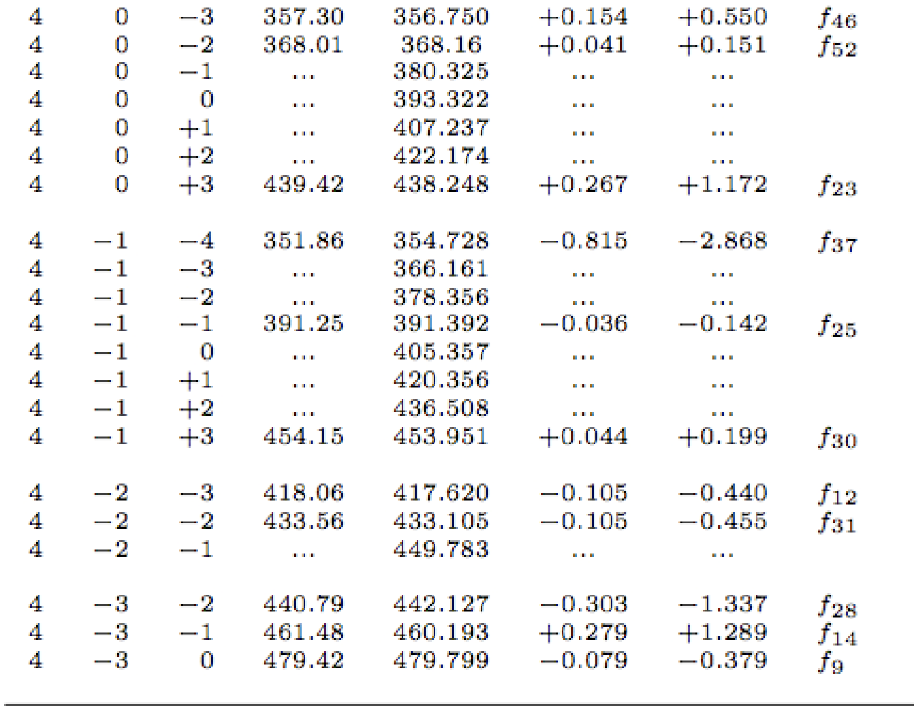
$\log g = 5.2783$

Period fit : $S^2 \sim 8.04 \Leftrightarrow \overline{\Delta P/P} \sim 0.21\%$ or $\overline{\Delta P} \sim 0.87$ s (excellent fit)

4. Asteroseismic analysis : Hypothesis of a fast rotation

Period fit and mode identification





l	k	m	$P_{\rm obs}$ (s)	$P_{\rm th}$ (s)	$\Delta X/X$ (%)	ΔP (s)	Comments
0	3	0	...	310.459	...	...	
0	2	0	364.60	365.062	−0.127	−0.462	f_4
0	1	0	...	450.589	...	...	
0	0	0	...	550.167	...	...	
1	1	−1	351.46	351.744	−0.081	−0.284	f_7
1	1	0	362.15	363.186	−0.286	−1.036	f_{17}
1	1	+1	...	375.397	...	...	
2	1	−2	...	407.403	...	...	
2	1	−1	...	422.829	...	...	
2	1	0	440.28	439.470	+0.184	+0.810	f_{16}
2	1	+1	...	457.474	...	...	
2	1	+2	475.82	477.015	−0.251	−1.195	f_3
2	0	−2	440.51	440.516	−0.001	−0.006	f_6
2	0	−1	...	457.487	...	...	
2	0	0	475.45	475.819	+0.078	−0.369	f_2
2	0	+1	...	495.681	...	...	
2	0	+2	...	517.274	...	...	
2	−1	−2	481.75	482.494	−0.154	−0.744	f_1
2	−1	−1	503.70	504.073	−0.074	−0.373	f_8
2	−1	0	528.70	527.672	+0.194	+1.028	f_5
2	−1	+1	...	553.59	...	...	
2	−1	+2	...	582.185	...	...	
2	−2	−2	...	523.886	...	...	
2	−2	−1	545.86	547.199	−0.245	−1.339	f_{38}
2	−2	0	573.26	572.683	+0.101	+0.577	f_{19}
2	−2	+1	...	600.657	...	...	
2	−2	+2	...	631.504	...	...	
4	1	−2	...	328.278	...	...	
4	1	−1	339.82	338.404	+0.417	+1.416	f_{29}
4	1	0	351.31	349.175	+0.608	+2.135	f_{18}
4	1	+1	361.49	360.654	+0.231	+0.836	f_{15}
4	1	+2	...	372.913	...	...	
4	1	+3	387.38	386.035	+0.347	+1.345	f_{33}
4	0	−3	357.30	356.750	+0.154	+0.550	f_{46}
4	0	−2	368.01	368.16	+0.041	+0.151	f_{52}
4	0	−1	...	380.325	...	...	
4	0	0	...	393.322	...	...	
4	0	+1	...	407.237	...	...	
4	0	+2	...	422.174	...	...	
4	0	+3	439.42	438.248	+0.267	+1.172	f_{23}
4	−1	−4	351.86	354.728	−0.815	−2.868	f_{37}
4	−1	−3	...	366.161	...	...	
4	−1	−2	...	378.356	...	...	
4	−1	−1	391.25	391.392	−0.036	−0.142	f_{25}
4	−1	0	...	405.357	...	...	
4	−1	+1	...	420.356	...	...	
4	−1	+2	...	436.508	...	...	
4	−1	+3	454.15	453.951	+0.044	+0.199	f_{30}
4	−2	−3	418.06	417.620	−0.105	−0.440	f_{12}
4	−2	−2	433.56	433.105	−0.105	−0.455	f_{31}
4	−2	−1	...	449.783	...	...	
4	−3	−2	440.79	442.127	−0.303	−1.337	f_{28}
4	−3	−1	461.48	460.193	+0.279	+1.289	f_{14}
4	−3	0	479.42	479.799	−0.079	−0.379	f_9

All f_1 to f_8 : $l \leq 2$

4. Asteroseismic analysis : Hypothesis of a fast rotation

Comments on structural parameters

> on X(C+O) and log (M_{core}/M_*)

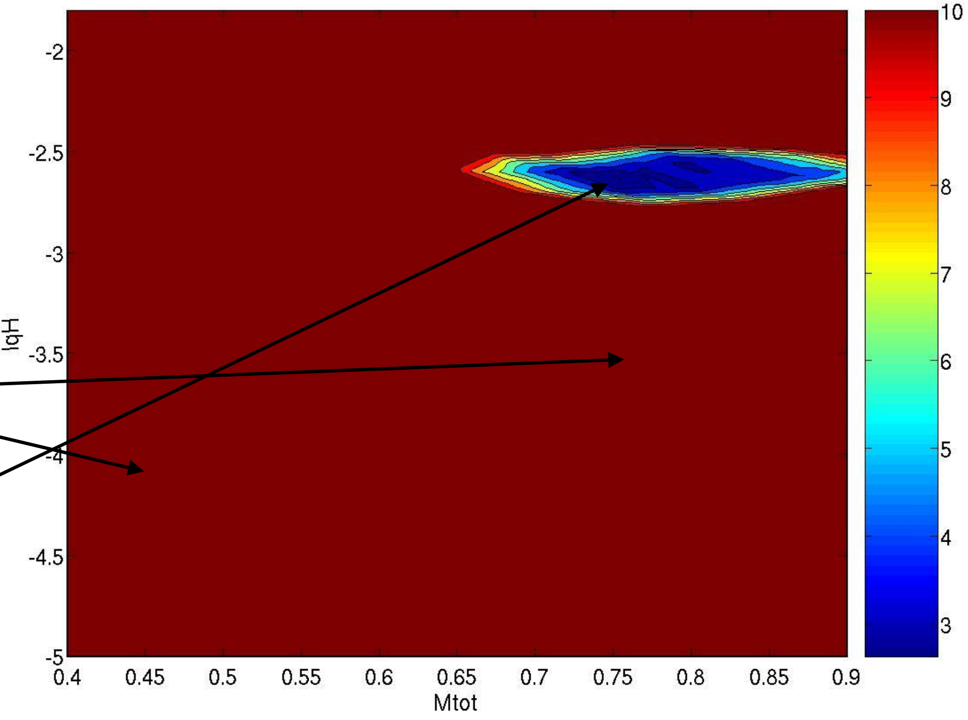
not consistent with external spectroscopic constraints

> on M_* and log (M_{env}/M_*)

not consistent with external spectroscopic constraints

M_{core} and X(C+O) are interdependant and not well defined (lack of sensitivity of pulsation modes to central regions)

quite well defined by pulsation spectrum and external spectroscopic constraints



A very-high mass model and thick envelope on EHB is found for PG 1605+072, consistent with the hypothesis of a fast rotation (~ 3 h)

5. Asteroseismic analysis : Comparison between the 2 hypotheses

Slow rotation

- $M_* = 0.7624\ M_s$
- $\log (M_{env}/M_*) = -2.6362$
- $(\log (M_{core}/M_*) = -0.0240)$
- $(X(C+O) = 0.45\ ;\ X(He) = 0.65)$

$T_{eff} = 32\,555$ K

$\log g = 5.2906$

Fast rotation

- $M_* = 0.7686\ M_s$
- $\log (M_{env}/M_*) = -2.7114$
- $P_{rot} = 11\,075\ \mathrm{s} = 3.076\ \mathrm{h}$
- $(\log (M_{core}/M_*) = -0.0722)$
- $(X(C+O) = 0.28\ ;\ X(He) = 0.72)$

$T_{eff} = 32\,723$ K

$\log g = 5.2783$

Similarity of model found in both cases !

(associated errors still have to be calculated)

- Star *structure* is very well defined (except core parameters)
- Star *rotation* not. Independent problems !

Remark : all the *m*=0 identified in the analysis with rotation belong to the 14 “basic frequencies” (NOT a hypothesis !)

6. Conclusion and raising questions

Conclusion :

We have found very high-mass and thick envelope model for PG1605+072 from asteroseismology

- Model consistent with a star on the EHB :
  - $M_* \sim 0.765\ M_s$
  - $\log (M_{env}/M_*) \sim -2.65$
  - $T_{eff} \sim$ 32 600 K
  - log g ~ 5.285

Raising questions :

✓ Is PG 1605+072 a fast rotator ? (asteroseismology cannot help on this question)

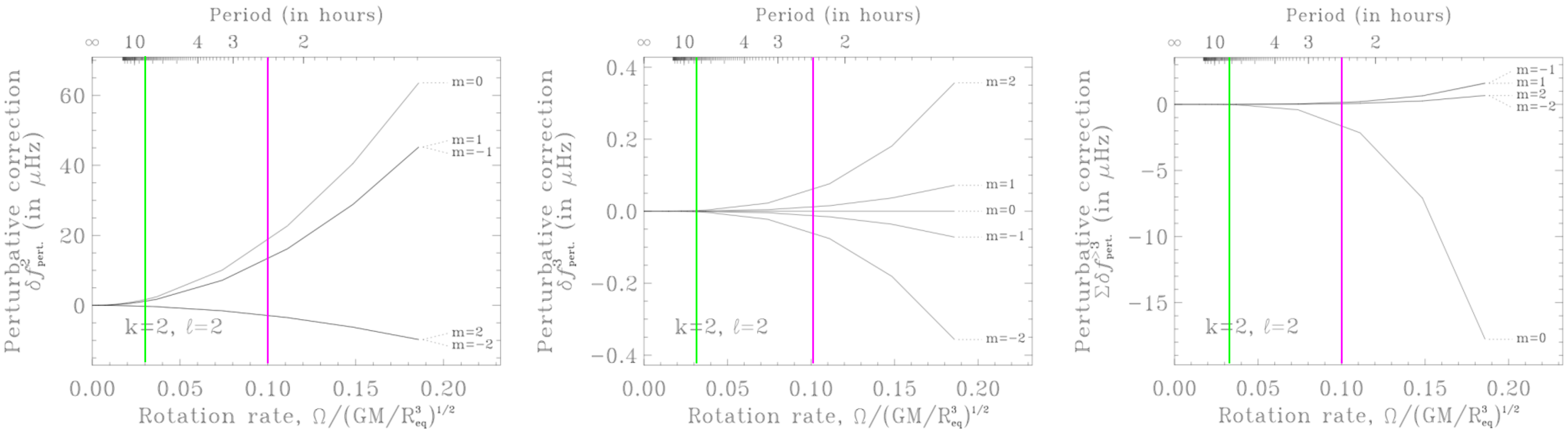
Line broadening = rotational broadening + pulsational broadening
in which proportions ?

✓ What is the formation channel for PG 1605+072 ???

- PG 1605+072 is most probably a single star
- We are “in the tail” of all formation channels ! (Han et al. 2002, 2003). Even “two WD merger” scenario

Validity of the 1st order perturbative approach

Evaluation of higher orders effects from polytropic (N=3) model of sdB star, with full treatment of rotation (work of D. Reese & F. Lignières)



2nd order

3rd order

higher orders

- Rotation period greater than ~ 9 h : 1st order completely valid
- Rotation period to ~ 2.5 h : corrections due to high orders (mainly 2nd order) have the same scale than the accuracy of asteroseismic fits (10 - 15 μHz)

Conclusion : 1st order perturbative approach valid for our purposes