The asteroseismic analysis of the pulsating sdB Feige 48 revisited

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1. Asteroseismological analysis : Method and Objectives

- **Forward approach** : fit theoretical periods with all observed periods simultaneously
  - Internal structure calculation from T_{eff}, log *g*, log q(H) (here after, lqh) and M_{tot}
  - Calculation of the adiabatic and non-adiabatic pulsations + rotational splitting calculation (see next slide)
  - Double-optimisation scheme to find the best fit(s)

$$S^2 = \Sigma\,(P_{obs} - P_{th})^2$$

- *A-posteriori* mode identification (*k, l*, *m*). For *l:* independent test from multi-colour photometry

Introduction of the star rotation

- $\Omega(r)$ rotation, 1st order Perturbative Theory:

$$\omega_{klm} - \omega_{kl} = \delta\omega_{klm} = m\frac{\int_0^R \Omega(r)(\xi_r^2 + L^2\xi_h^2 - 2\xi_r\xi_h - \xi_h^2)\rho r^2 dr}{\int_0^R (\xi_r^2 + L^2\xi_h^2)\rho r^2 dr}$$

where $y_1 = \frac{\xi_r}{r}$ and $y_2 = \frac{\omega^2}{g}\xi_h$ Dziembowski's variables are given by pulsation codes. For each theoretical (adiabatic) period *m* = 0, calculation of the multiplets for a given $\Omega(r)$ (solid, fast core or linear rotation). Advantage :

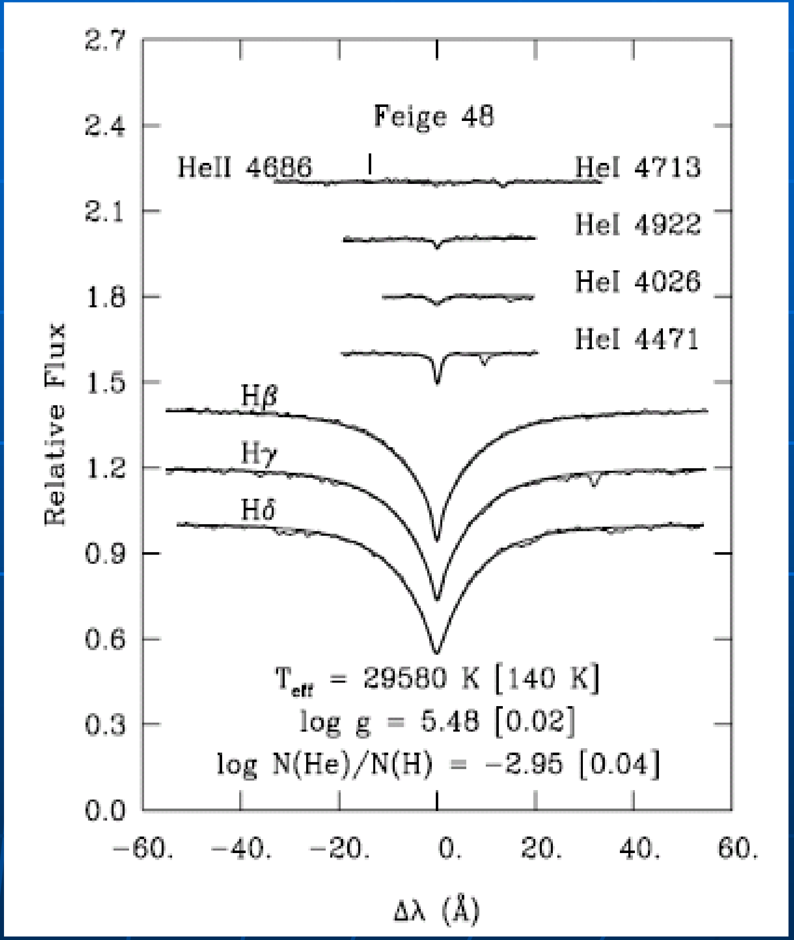
All observed periods can be used for analysis, no need for assumptions about *m* = 0 modes

2. What is known so far about Feige 48

Feige 48 : Spectroscopy

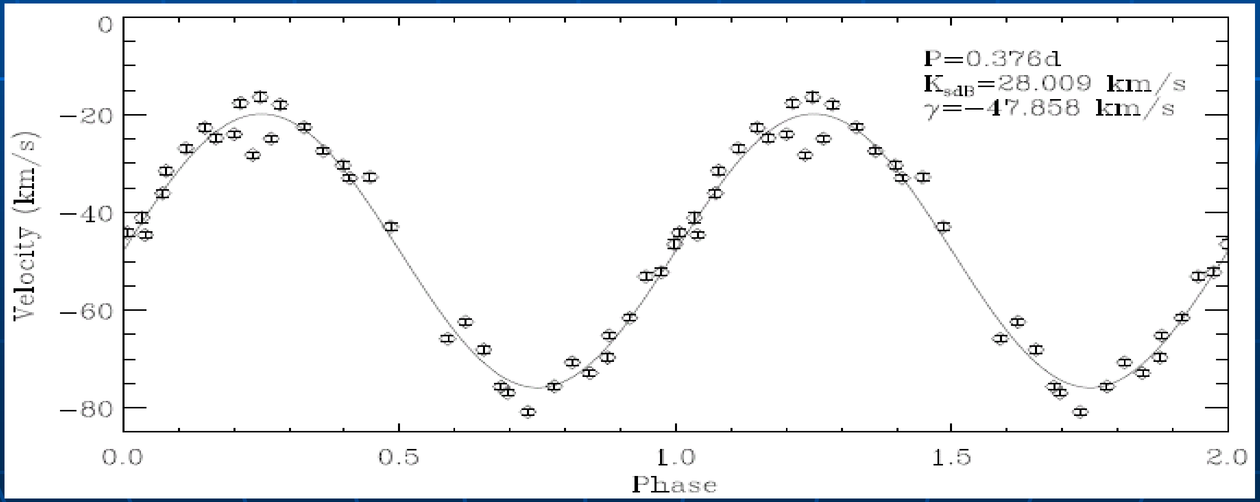
- Koen et al., 1998
  - T_{eff} = 28,900 ± 300 K
  - log g = 5.45 ± 0.05
- Heber et al., 2000, Keck/HIRES
  - T_{eff} = 29,500 ± 300 K
  - log g = 5.50 ± 0.05

    + $V \sin i \leq 5$ km s^{-1}
- Charpinet et al., 2005, MMT
  - T_{eff} = 29,580 ± 370 K
  - log g = 5.480 ± 0.046



Feige 48 : a close binary system

- S. O'Toole et al., 2004: *Detection of a companion to the pulsating sdB Feige 48.* HST/STIS, FUSE archives
  - Velocity semi-amplitude K_{sdB} = 28.0 ± 0.2 km s^{-1}
  - Orbital period of 0.376 ± 0.003 d (⇔ 9.024 ± 0.072h)
  - The unseen companion is a white dwarf with ≥ 0.46 M_s
  - Orbital inclination *i* ≤ 11.4°



Feige 48 : time-series photometry

- CFHT, six nights in June 1998. Resolution of ~ 2.18 μHz
- 9 periods detected:

ID	Frequency (mHz)	Period (s)	Amplitude (%)	Spacing (μHz)	Reed et al. (2004) Period (s)
f_1^+	2.91522	343.027	0.071	+25.0	...
f_1	2.89020	345.997	0.111	...	(346.01)
f_2^+	2.90640	344.068	0.411	+28.9	344.08
f_2	2.87745	347.530	0.640	...	347.56
f_2^-	2.85107	350.746	0.165	−26.4	350.75
f_3	2.83728	352.450	0.116	...	352.40
f_4^+	2.67180	374.280	0.039	+29.5	...
f_4	2.64228	378.461	0.131	...	378.50
f_4^-	2.61105	382.988	0.043	−31.2	...

Spacing of 52.9 μHz with f_1 (Δm=2) !!!

- Mean spacing: <Δν> ~ 28.2 μHz, σ(Δν) = 2.48 μHz

Feige 48 : first asteroseismic analysis
Charpinet et al., A&A 343, 251-269, 2005

- Assumption of 4 $m = 0$ modes, no rotation included
- Only degrees $l \leq 2$
- Structural parameters obtained:

  T_{eff} = 29 580 ± 370 K (fixed), log g = 5.4365 ± 0.0060,

  lqh = -2.97 ± 0.09 and M_{tot} = 0.460 ± 0.008 Ms
- Period fit : <dp/p> ~ 0.005%, <dp> ~ 0.018s, close to the accuracy of the observations !
- Derived inclination $i \leq 10.4 \pm 1.7°$, very good agreement with O'Toole et al.

First Asteroseismic analysis: Mode Identification

ℓ	k	$P_{\rm obs}$ (s)	$P_{\rm th}$ (s)	σ_I (rad/s)	Stability	log E (erg)	$C_{k\ell}$	$\Delta P/P$ (%)	ΔP (s)	Comments
0	5	...	157.185	$+4.926\times 10^{-5}$	stable	39.922	...	...	...	
0	4	...	173.311	$+9.511\times 10^{-6}$	stable	39.948	...	...	...	
0	3	...	201.344	-3.640×10^{-5}	unstable	40.227	...	...	...	
0	2	...	238.081	-3.397×10^{-5}	unstable	40.494	...	...	...	
0	1	...	294.372	-7.854×10^{-6}	unstable	41.098	...	...	...	
0	0	352.450	352.418	-8.974×10^{-7}	unstable	41.886	...	+0.009	+0.032	f_3: singlet
1	5	...	171.935	$+1.510\times 10^{-5}$	stable	39.899	0.0068	...	...	
1	4	...	200.363	-3.608×10^{-5}	unstable	40.216	0.0064	...	...	
1	3	...	237.079	-3.455×10^{-5}	unstable	40.483	0.0089	...	...	
1	2	...	292.489	-8.095×10^{-6}	unstable	41.086	0.0140	...	...	
1	1	347.530	347.530	-5.044×10^{-7}	unstable	42.027	0.0306	0.000	0.000	f_2: triplet
1	1	...	597.094	-3.984×10^{-13}	unstable	47.011	0.4055	...	...	
2	5	...	169.233	$+2.636\times 10^{-5}$	stable	39.848	0.0202	...	...	
2	4	...	194.678	-2.335×10^{-5}	unstable	40.275	0.1221	...	...	
2	3	...	206.733	-1.444×10^{-5}	unstable	40.645	0.2239	...	...	
2	2	...	236.054	-3.379×10^{-5}	unstable	40.486	0.0114	...	...	
2	1	...	289.169	-8.455×10^{-6}	unstable	41.068	0.0071	...	...	
2	0	345.997	345.960	-1.200×10^{-7}	unstable	41.763	0.0130	+0.011	+0.037	f_1: doublet
2	1	378.461	378.465	-3.938×10^{-9}	unstable	44.025	0.0820	−0.001	−0.004	f_4: triplet

3. New asteroseismological analysis with rotation

Search for the optimal model with solid rotation

- Solid Rotation: hypothesis
- No assumption about $m = 0$ modes (used all 9 periods); still only degrees $l \leq 2$; no *a-priori* constraint on identification
- Optimisation on 4 parameters : log g, lqh, M_{tot} and P_{rot}
- Several models* can fit the 9 periods, the preferred one is:

  T_{eff} = 29 580 ± 370 K (still fixed), log g = 5.4622 ± 0.0060,
  lqh = -2.58 ± 0.09 and M_{tot} = 0.519 ± 0.008 Ms
- Solid rotation P_{rot} = 32 500s ± 2200s ⇔ 9.028 ± 0.61h Excellent agreement with orbital period determined independently from velocities variations (P_{orb} = 9.024 ± 0.072h).
- Period fit : $S^2 \sim 0.60$ ⇔ <dp/p> ~ 0.06%, <dp> ~ 0.22s

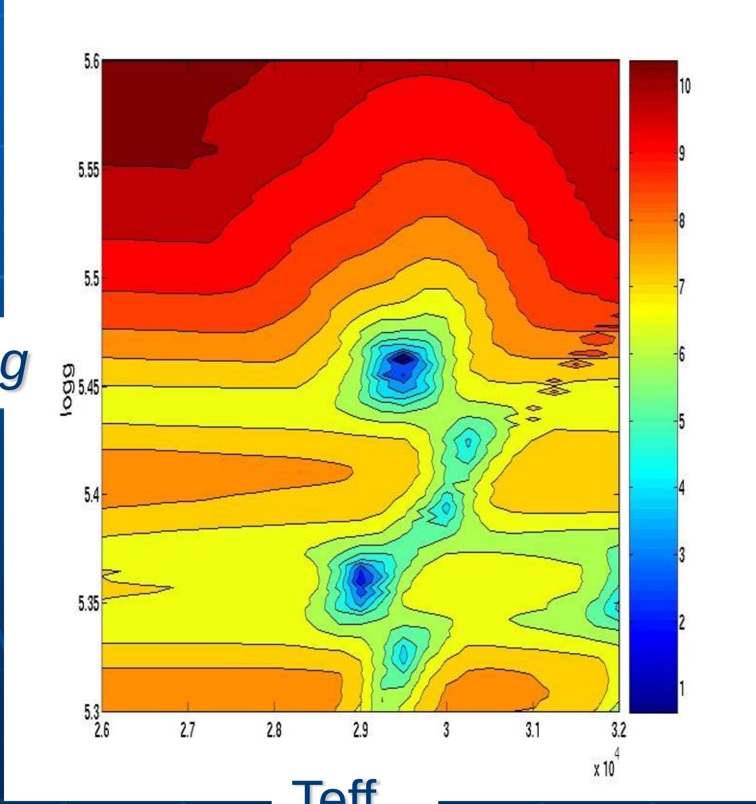
Analysis with solid rotation: Mode Identification

l	k	m	P_{obs} (s)	P_{th} (s)	$\Delta P/P$ (%)	$\Delta\nu_{calc}$ (μHz)	$\Delta\nu_{obs}$ (μHz)	Comments	R : Amplitude (%)
0	2	0	...	237.539	...	...	...		
0	1	0	...	292.924	...	...	...		
0	0	0	352.450	352.072	0.107	...	...	independent	0.116
1	2	+1	...	288.066	...	30.36	...		
1	2	0	...	290.608	...	30.36	...		
1	2	−1	...	293.194	...	30.36	...		
1	1	+1	344.068	344.116	−0.0141	28.62	28.90		0.411
1	1	0	347.530	347.540	−0.0028	28.62	...	$\sharp$1, triplet	0.640
1	1	−1	350.746	351.032	−0.0815	28.62	26.40		0.165
2	1	+2	...	280.775	...	30.59	...		
2	1	+1	...	283.208	...	30.59	...		
2	1	0	...	285.683	...	30.59	...		
2	1	−1	...	288.202	30.59	...	...		
2	1	−2	...	290.766	30.59	...	...		
2	0	+2	...	332.382	...	30.32	...		
2	0	+1	...	335.766	...	30.32	...		
2	0	0	...	339.219	...	30.32	...		
2	0	−1	343.027	342.744	+0.0824	30.32	25.02	doublet	0.071
2	0	−2	345.997	346.343	−0.1001	30.32	...		0.111
2	1	+2	...	366.704	...	28.40	...		
2	1	+1	...	370.563	...	28.40	...		
2	1	0	374.280	374.504	−0.0598	28.40	29.5		0.039
2	1	−1	378.461	378.529	−0.0181	28.40	...	triplet, g-mode	0.131
2	1	−2	382.988	382.643	+0.0902	28.40	31.2		0.043

Space parameters maps

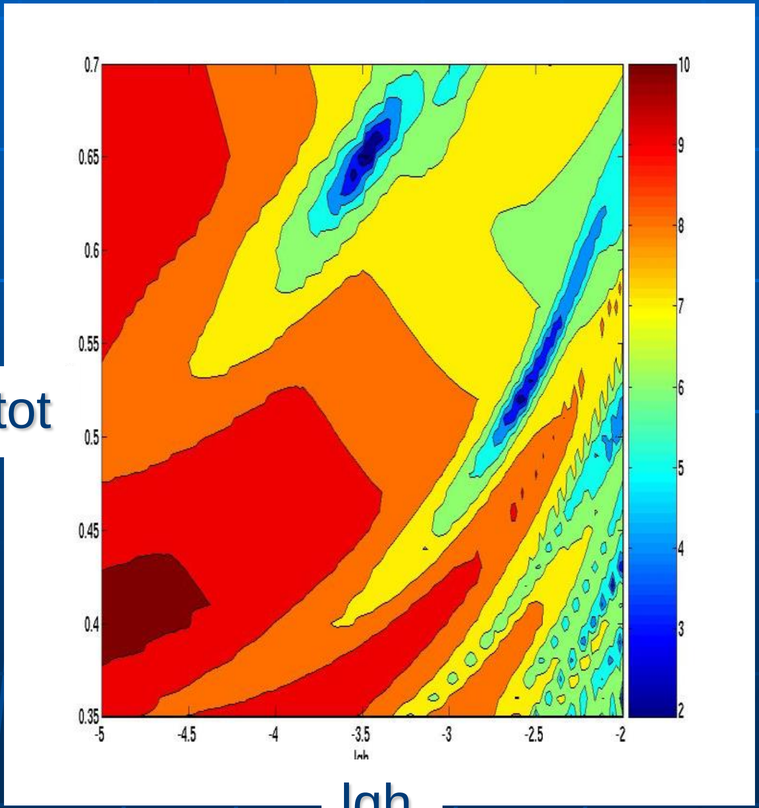
- Left : lqh and M_{tot} fixed; right : T_{eff} and log *g* fixed

log *g*



Teff

Mtot



lqh

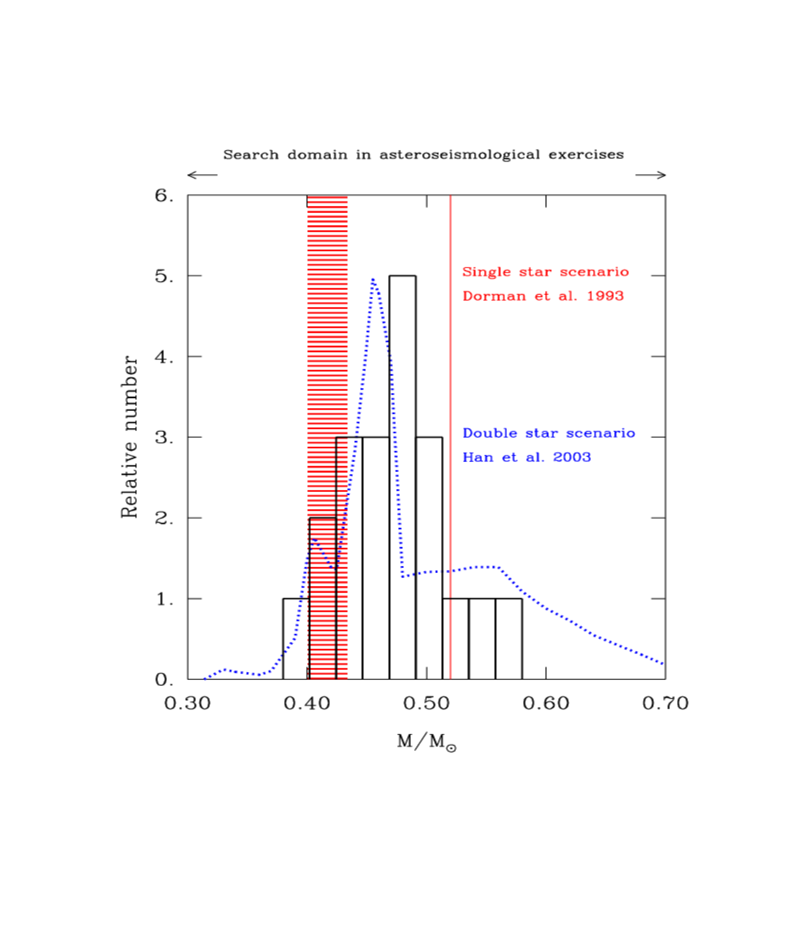
Comparison with Charpinet et al., 2005

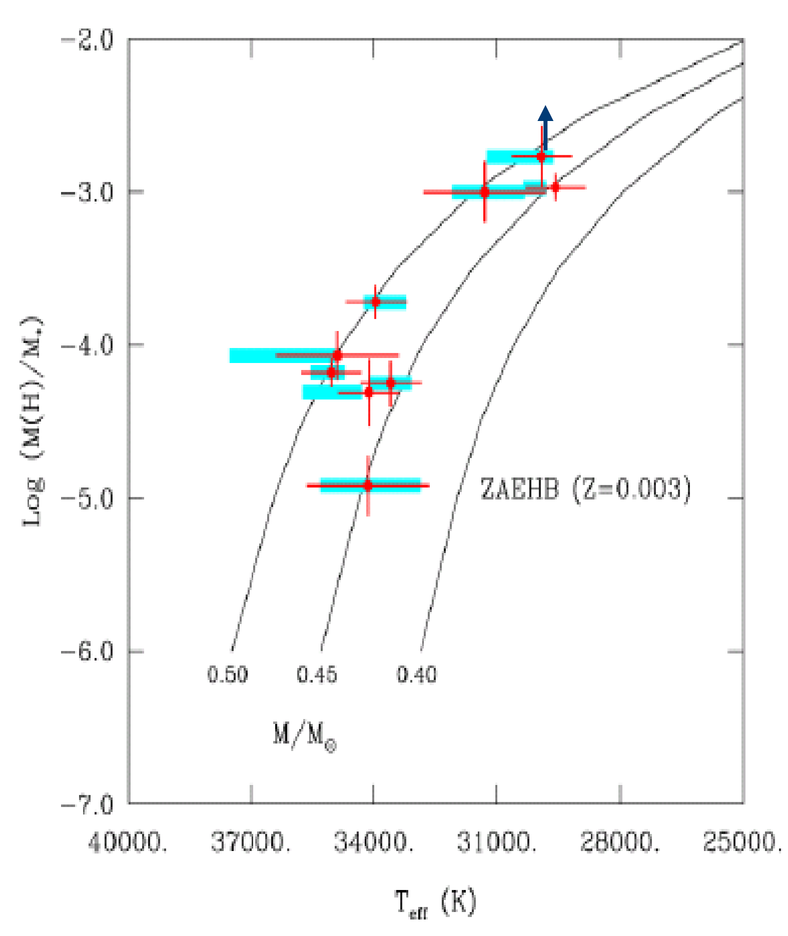
- About model parameters:
  - New surface gravity log *g* closer to spectroscopy
  - Total mass relatively high (M_{tot} ~ 0.52 M_s) but *possible* according to Han's simulations (2003)
  - H-envelope slightly thicker, still completely consistent with Stellar Evolution Theory

- About period fit and mode identification:
  - The difference is about the *m* = 0 modes in the doublet (343-346s) and the triplet (374-378-383s). The identification "*m* = -1, *m* = -2" is maybe unexpected, but the intrinsic amplitudes are never known
  - Forcing Charpinet's model + solid rotation : S^2 ~ 2.6 (4x poorer). No convergence to a Rotation Period of ~ 32 500s (rather ~ 29 500s)

Conclusion : Charpinet's model is not given up, but there is also hints in favor of a higher mass model

Consistency with Han's simulations and EHB Stellar Evolution Theory





Comparison with Charpinet et al., 2005

P_{obs} (s)	l	k	m
343.027	2	0	−1
345.997	2	0	−2
344.068	1	1	1
347.530	1	1	0
350.746	1	1	−1
352.450	0	0	0
374.280	2	1	0
378.461	2	1	−1
382.988	2	1	−2

$S^2 \sim 0.6$
$\log g \sim 5.46$
$M_{tot} \sim 0.52\ M_s$
$P_{rot} \sim 32{,}500$s

l	k	m
2	0	0
2	0	−1
1	1	1
1	1	0
1	1	−1
0	0	0
2	1	0
2	1	−1
2	1	−2

$S^2 \sim 0.9$
$\log g \sim 5.45$
$M_{tot} \sim 0.49\ M_s$
$P_{rot} \sim 30{,}500$s

l	k	m
2	0	1
2	0	0
1	1	1
1	1	0
1	1	−1
0	0	0
2	1	1
2	1	0
2	1	−1

$S^2 \sim 2.6$
$\log g \sim 5.435$
$M_{tot} \sim 0.46\ M_s$
$P_{rot} \sim 29{,}500$s

Suggestion : time-series spectroscopy observations could give (needed) hints about *m*

Comments about the period of solid rotation (= 9.028 ± 0.61h)

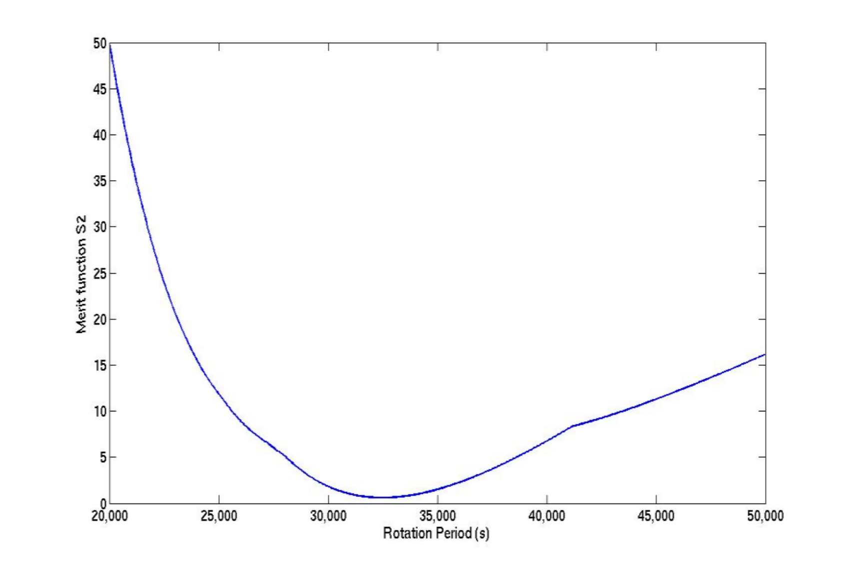
- Fitting all 9 periods independently is impossible (very poor S^2 and no convincing models) → not a slow rotator
- The smallest Δf is 8.82 µHz (⇔ P_{rot}~1.2 days at the *slowest*), but again convincing models don't exist at this rate
- Even without knowing the orbital period, ~ 9.5h is the only acceptable rate for the rotation period

Conclusion :

Orbital period = Rotation period

(even if lower accuracy for P_{rot})

→ Confirmation of the reasonable assumption of a tidally locked system

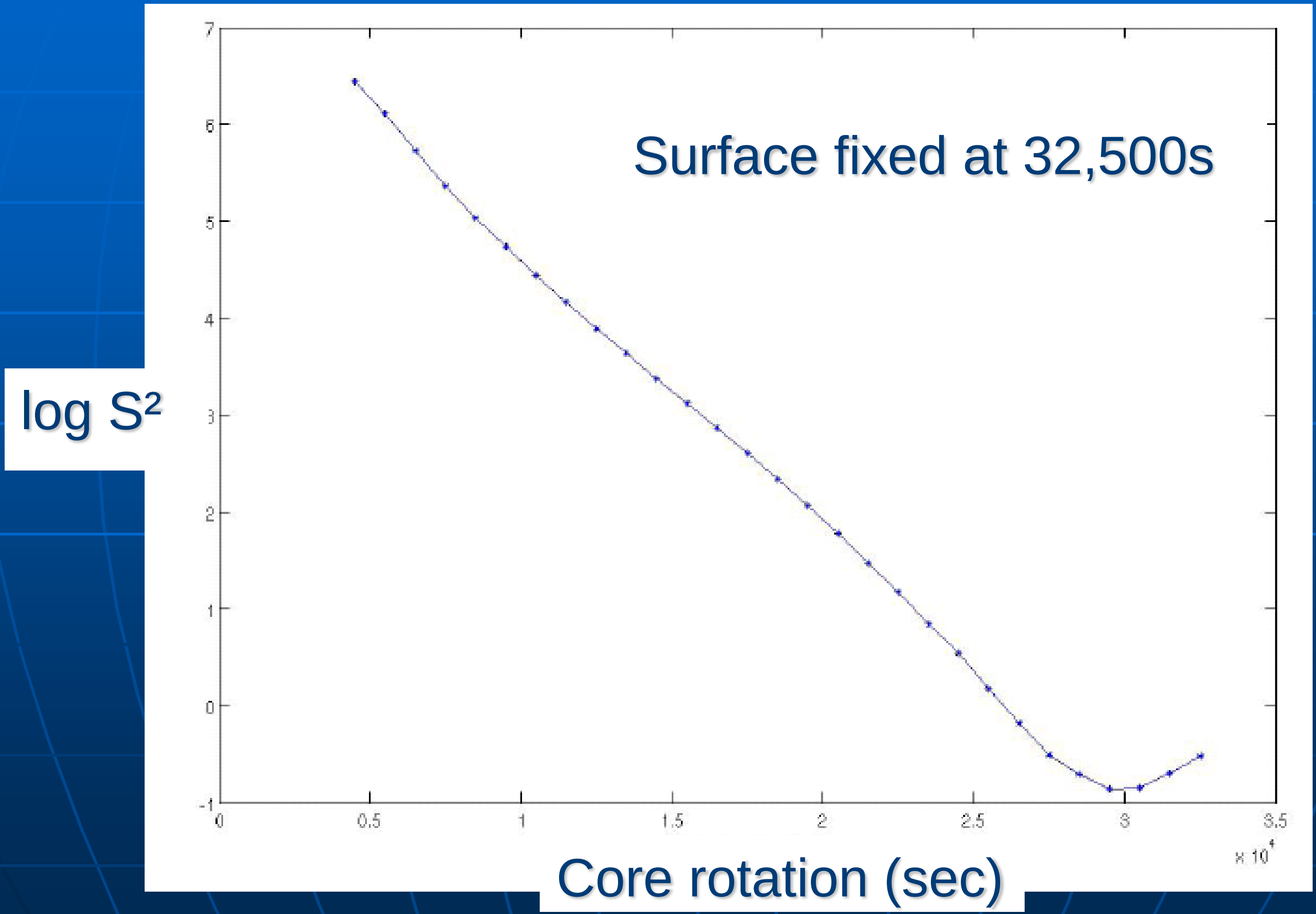


4. Testing the hypothesis of a fast core rotation

4. Testing a fast core rotation
(Kawaler et al. ApJ 621, 432-444, 2005)

- Reminder : only degrees *l* ≤ 2 for this star
  → ideal to test the hypothesis of a fast core
- Surface rotation fixed at the optimal value of 32,500s. Core rotation was varied from 500 to 32,500s, by steps of 500s. For each core period, computing merit function S^2
- Transition fixed at 0.3 R* (following Kawaler et al., 2005)

Testing a fast core rotation



Conclusions and room for improvement

- We determined an « alternative » convincing model for Feige 48 by adding the rotation as a free parameter. This rotation is found to be solid with a period of ~ 9.028h (equals to orbital period), which confirms that the system is tidally locked. A fast core rotation can be excluded for this star.

- Room for improvement:
  - Better observations (more pulsations modes <u>and</u> better resolution) are needed to confirm/reject the results (and choose between the models…)
  - Multi-colour photometry to confirm degrees *l* (particularly *l* = 0 or 2 for 352s mode)
  - Ultimate test: time-series spectroscopy to confirm/reject the *l* and *m* values inferred

Thank you for your attention !

Testing a fast core rotation

- Apparently slight differential rotation: best S^2 obtained for P_{core} ~ 29,500s (and P_{surf} = 32,500s)
- BUT not significant:
  - *g* and *f*-modes are very sensitive to a fast core rotation, while most p-modes are not (except « marginal » ones)
  - The triplet 374-378-382s, identified as the *g*-mode « $l = 2$, $k = 1$ », shows Δf of 29.5µHz and 31.2µHz, above the mean spacing of 28.2µHz. This is better reproduced with a fast core rotation. But these higher Δf are not significant with a resolution of 2.17µHz !

Conclusion : a fast core rotation is impossible for Feige 48, which has probably a solid rotation !