ROMOSC

between
MOST and COROT

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ROMOSC. Introduction

ROMOSC is an inverse (seismic) method implemented in Bucharest Observatory:

- prepared for CoRoT space mission

and

- calibrated with MOST and ground data

in this paper, with

- minimal physics
- minimal parameters to be determined

but self-consistent enough (from the point of view of seismic excitability) to be applied to:

- different pulsating stars (δ Scuti, B/SPB, pre/postms).

Methods of studying pulsating stars

- Direct method:
  $P^{th} = K[M(S)]$
- Comparison with observations:

  $P^{th} - P^{obs} = L[M(S)] \rightarrow 0$
- Inverse methods (asteroseismological methods):

$$M(S) = \mathbf{min}\ (L^{-1}[P^{th} - P^{obs}])$$

where we have:

- **Space of equations**: $P = [\nu_{nlm}, A_{\nu,nlm}, \Phi_{\nu,nlm}, (lpv)_{\nu,k}, \Delta_{nlm}, \delta_{nlm}]$
- **Space of parameters**: $M = [(M, t_0)\ \{X, Y, Z_j^{Nz}\}, \alpha_{MLT}, (i, v_{r,0})\ (D^{Nd}, \ldots.)] =$
  $= [(M, T_e)\ \{X, Y, Z_j^{Nz}\}, \alpha_{MLT}), (D^{Nd}, \ldots.)]$
- **Space of solutions**: $S = [X_i, Y_i]$ (stellar + pulsation)

$X_i = [p, T, r, L, \rho, \kappa, \varepsilon, C_V, C_P, \Gamma_1, \Gamma_3, L_{rad}, \nabla_{ad}, \nabla_{rad}, \nabla, \partial_T\kappa, \partial_\rho\kappa\ \partial_T\varepsilon, \partial_\rho\varepsilon, \delta, \alpha, d\rho/dr]_i$

$Y_i = [(y_1, \ldots, y_6), \omega, \eta(\equiv\omega_I/\omega_R), (A, \phi^{r,L,T,p})]_{i,nlm}$ $\quad i = 1, N$

Stellar inversion method

Asteroseismological method: (O-C)[2] method:

$$\boldsymbol{min}\ X^2 = \boldsymbol{min}(\Sigma\ [P^{th} - P^{obs}]^2) \rightarrow M(S),$$

with the conditions:

- consistent solution: $Nr(P) >> Nr(M)$
- in the range of observed T_e: $T_e \in [T_e^{obs} - \Delta T, T_e^{obs} + \Delta T]$

- either – with assumed evolutionary status: $t \in [t1, t2]$;
- or – in the range of observed L: $L \in [L_{obs} - \Delta L, L_{obs} + \Delta L]$;

- and with excited and stable modes: $Im(\omega) \rightarrow \eta_{nlm} = \frac{W}{\int_0^1 \left|\frac{dW}{dx}\right| dx} > 0$

ROMOSC seismological method

In order to test the abilities of ROMOSC software package
➔ROMOSC first step - minimal approximation:

- P = [$\nu_{n,l}$] (without rotation and magnetic field);
- M = [(M, t) {X, Y, Z}] (simple set of parameters);
- S = [X_i, Y_i];

ROMOSC seismological method

Software package:

- CESAM2k_V2 – evolutionary model/track (Morel 2005, private com);

$$\begin{cases} \frac{dx_i}{dr} = f(x_i, q_i) \\ \frac{\partial X_i}{\partial t} = \Psi(X_i) \\ q_i = q_i(x_i, X_i) \end{cases}$$

- automated interface - evolutionary – pulsationary models /track;

$$X(r,t) \Rightarrow A(r,t)$$

- LNAWENR/track-pulsationary model: linear+nonradial+nonadiabatic; (Suran 1991, Ro.A.J);

$$\begin{cases} r\frac{dy}{dr} = A(r, t_0 \mid \omega) y \\ D(\omega, y) = 0 \end{cases} \Rightarrow \begin{cases} \left[\theta A^{i+\frac{1}{2}} + \alpha_i\right] y_i + \left[(1-\theta) A^{i+\frac{1}{2}} - \alpha_{i+1}\right] y_{i+1} = \gamma_i \\ \omega_{i+2} = \frac{\omega_{i+1} D_i(\omega, y) - \omega_i D_{i+1}(\omega, y)}{D_i(\omega, y) - D_{i+1}(\omega, y)} \end{cases}$$

- Henyey type
- /ev. track

- inverse method/grid of tracks ➔ asteroseismological best fit (O-C)^2;

$$\chi^2 = \frac{1}{N}\sum_{i=1}^{N}(\nu_{O,i} - \nu_{C,i})^2$$

- Additional software for visualizations, internal structure and modes determination and plotting .

ROMOSC seismological method

ROMOSC perform two different tasks:

- The building of a grid of theoretical tracks;
- For each star, to use this grid in the asteroseismological best fit $(O-C)^2$.

Hardware (Bucharest) special designed:

- SGI/ALTIX Itanium 2, 4 processors, 24Gflops, 12 Gb RAM, 250 Gb HDD;
- ROMOSC/track ➔ ~ 1.2 Gb;
- ROMOSC/track ➔ > 3h /proc. (evol + puls (t));
- 4 independent lines for tracks determination (= 4 proc. for grid building);

ROMOSC seismological method

To calibrate ROMOSC - simple conditions:

- Cesam2k_V2: without diffusion; α_{MLT}=1.6;
- Cesam2k_V2:abundances: Grevesse@Noels;
- Cesam2k_V2:opacities: Yveline (Opal+Alexander);
- Cesam2k_V2:eos:OPAL2001;

- LNAWENR: without Richardson interpolation scheme;
- LNAWENR: with zero pressure upper boundary condition ($y_1-y_2+y_3=0$).

ROMOSC calibration

- **η Boo** - δ Scuti type – MOST + ground (low + high p modes);
  - excitation mechanism?
  - M+ground connection?
- **HD 163830** - B (SPB) type – MOST (high g modes);
  - excitability?
  - rotation?
- **V351 Ori** - δ Scuti pre/post MS type – ground (low p modes)
  - pms/postms?

η Boo

- Excitation mechanism? Solar stochastic like?
- MOST modes identification?
- Connection between MOST and ground observed modes?

η Boo. Input physical data

- **η Boo: G IV, V=2.68, d=46.7±1.9 pc.**

- $T_e^{Di\ Mauro}$ = 6028±45 K L/L$_{\odot}$ = 9.01 ± 0.2
- $T_e^{Felting}$ = 6000 ± 100 K
- $T_e^{Bedding}$ = 6050 ± 60 K L/L$_{\odot}$ = 9.02 ± 0.22
- $T_e^{Thevenin}$ = 6050 ± 150 K L/L$_{\odot}$ = 8.95 ± 0.20 R/R$_{\odot}$ = 2.68 ± 0.05
- T_e^{Cayrel} = [5943,6219] K

η Boo

High precision stellar modeling and rigorous asteroseismic tests for *p* and *g* modes:

- Observations:
  - MOST space mission (*g* and *p* modes 100< ν_i <700 μHz, *l*=0) (M);
  - Kjeldsen (*p* modes, 600< ν_i <1000 μHz, *l*=0-2) (K);
  - Carrier (*p* modes, 600< ν_i <1000 μHz, *l*=0-2) (C);
  - ➔ ~ 40 frequencies.
  - HIPPARCOS astrometry: Bedding 1997 ;
  - Interferometry: VLTI/VINCI, Thevenin et al. 2005;
- Theory:
  - Guenther et al. 2005 (M, M+K, M+C) ;
  - Straka et al. 2005 (M, with turbulence);
  - Kjeldsen et al. 1994-2006 (K).

η Boo

References

- Bedding, T.R. 1997, astro-ph/9709005;
- Carrier, F., Eggenberger, P., Bouchy, F. 2005, A&A, 434,550 (C);
- Di Mauro, M.P., Christensen-Dalsgaard, J., Kjeldsen, H.,Bedding, T.R., Paterno, L. 2003, A&A,404, 341;
- Guenther, D.B. 2004, Ap.J., 612,454;
- Guenther, D.B., Brown, K.I.T. 2004, Ap.J., 600, 419 (QDG);
- Guenther, D.B., Kallinger, T., Reegen, P., Weiss, W. W., Matthews, J.M., Kusching, R., Marchenko, S., Moffat, A. F. J, Rucinski, S.M., Sasselov, D., Walker, G.A.H. 2005, astro-ph/0508449 (M);
- Kjeldsen, H., Bedding,T.R., baldry, I.K. Bruntt, H., Buthler, R.P., Fischer, D.A., Frandsen, S., Gates, E.L. 2003, A.J.,126,1483 (K);
- Straka, C., Demarque, P., Guenther, D.B., Li, L., Robinson F.J. 2005, astro-ph/0509403;
- Thevenin, F., Kervella, P., Pichon, B., Morel, P., di Folco, E., Lebreton, Y. 2005, A&A, 436, 253;

η Boo

Our calculations:

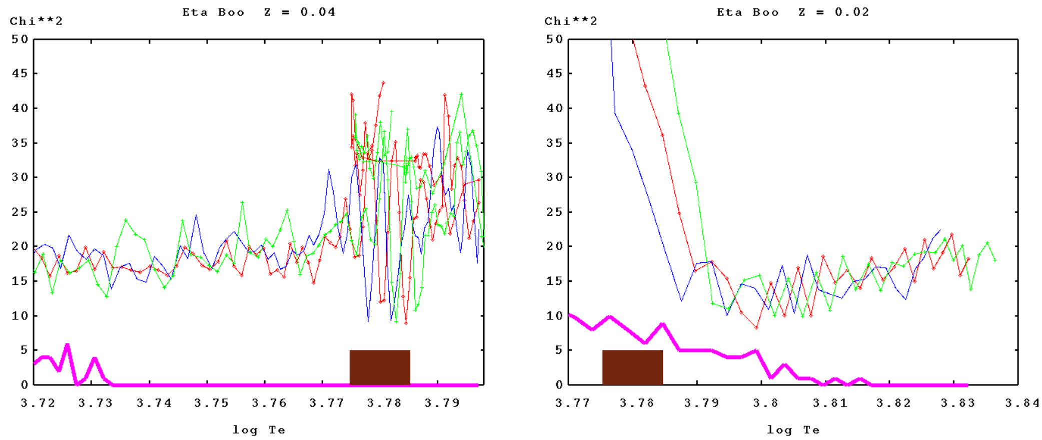
- **Calibration COROT/MOST ←→ CESAM+ROMOSC/YREQ+QDG**

  – **40 observed modes M+K+C** (*g*, *p*, *l*=0-2);
  – **8 observed modes M** (*p*, *l*=0);
  – **8 observed modes K** (*p*, *l*=0);

  – χ^2 minima for a grid of tracks:
    - M = 1.60 $M_\odot$ - 1.75 $M_\odot$; grid step 0.005 $M_\odot$ for (M+K+C, 40 modes);
    - M (8), K(8,l=0) on the same stellar track as minima χ^2 for (M+K+C)
    - Z = 0.02, 0.03, 0.04;

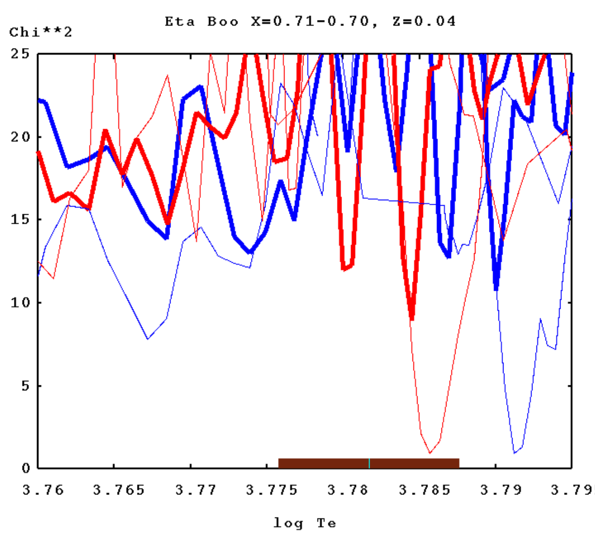
  – range of effective temperature: 6050 ± 60K;

η Boo



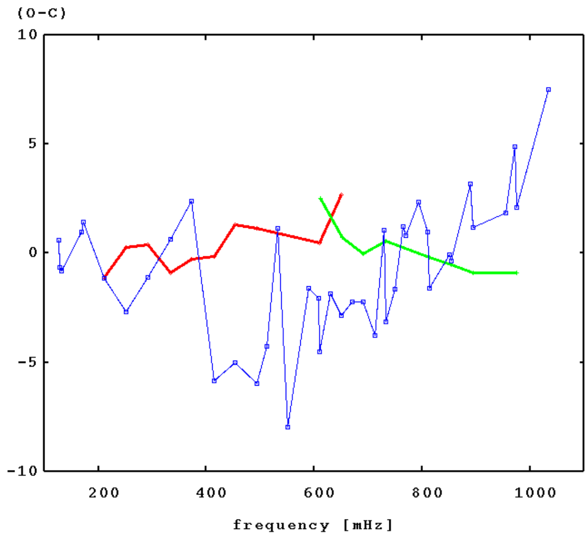
The minima of the χ2 as function of log(Te), calculated using the observed modes for the star η Boo (40 modes M+K+C) and the evolutionary postms tracks of 1.70 M⊙ (blue) ,1.71 M⊙ (red), 1.72 M⊙ (green). Up: Z = 0.04. Down: Z = 0.02. The deepest minima of χ2 corresponds to the star of 1.71M⊙ , Z =0.04. In brown is indicated the observed zone in temperature for the star η Boo: 6050 ± 60 K. In magenta is indicated the corresponding number of modes excited but unstable, from the 40 modes taken into account for the star η Boo (zero means all modes excited and stable).

η Boo



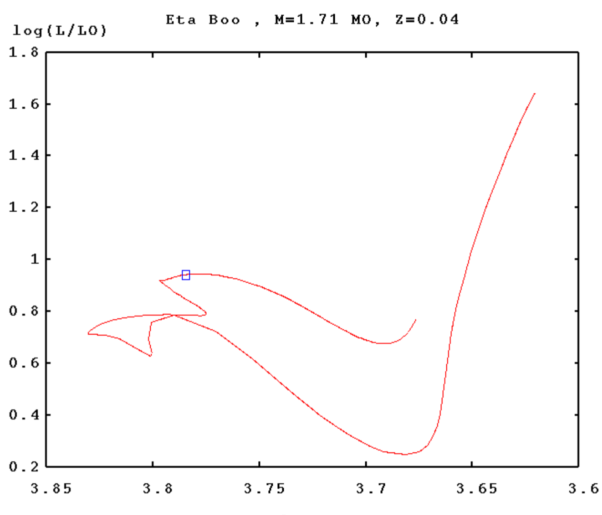
The minima of the χ2 as function of log(Te), calculated using the observed modes for the star η Boo. Thick lines are for all 40 modes (M+K+C), thin lines are for 8 modes (M, see Guenther et al. 2005). The evolutionary postms track are for a star of 1.71 M⊙ , Z = 0.04, X = 0.71 (red) and X = 0.70 (blue).
In brown is indicated the observed zone in temperature for the star η Boo: 6050 ± 60 K.

η Boo



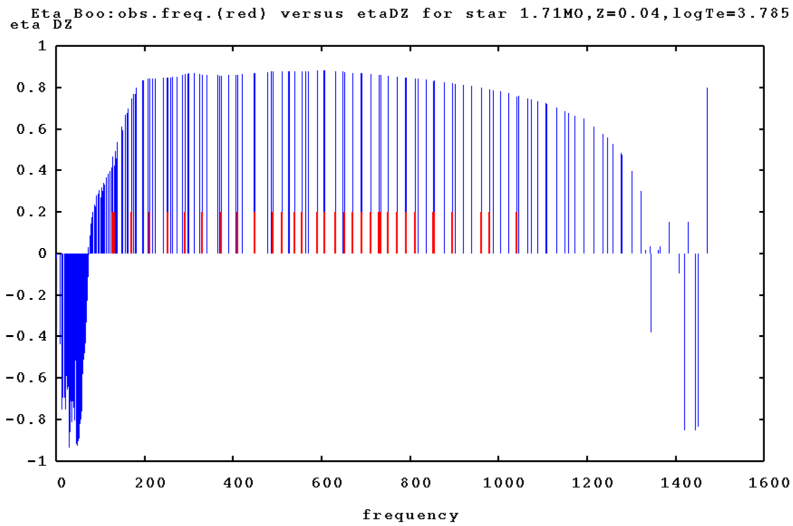
The <|(O-C|> as function of frequencies, calculated using the observed modes for the star η Boo.
Blue - 40 modes M+K+C red - 8 modes M, green - 8 modes K.

η Boo



Evolutionary tracks in the HR diagram for a star of 1.71 M⊙ , Z = 0.04 star in diagram HR.
Also, in the diagram the position of the star η Boo is indicated.

η Boo



The spectra of the observed modes for the star η Boo (40 modes M+K+C; in red) compared with the theoretical ones (η in blue) for a star of 1.71M☉, Z=0.04.

η Boo

Parameter	Bucharest Min I [40 modes, M+K+C] A.	B.	Bucharest Min II [8 modes, M]	Bucharest Min III [8 modes, K, *l*=0]	Guenther with turbulence 1.	Guenther without turbulence 2. 8 modes
χ^2	8.28	9.29	0.96	1.12	<1*	1.31*
$M/M_\odot$	1.71	1.71	1.71	1.71	1.71	1.71
Z	0.04	0.04	0.04	0.04	0.04	0.04
T_e (K)	6080.	6025.	6105.	5974.	6028.	6078.
$L/L_\odot$	8.80	8.83	8.77	8.82	9.03	8.83
$R/R_\odot$	2.68	2.74	2.78	2.40		
t(Gyr)	2.37	2.38	2.35	2.41		2.40

(O-O)(15,K-C)~3.1 *(O-C)~3* *(O-C)<* 1 *(O-C)<* 1

HD163830

- Excitability of very high *g* modes ($\nu < 4$ mHz)?
- Rotational splitting?

HD163830

- Slowly pulsating B (SPB) star;
- V=9.3;
- B5II/III;

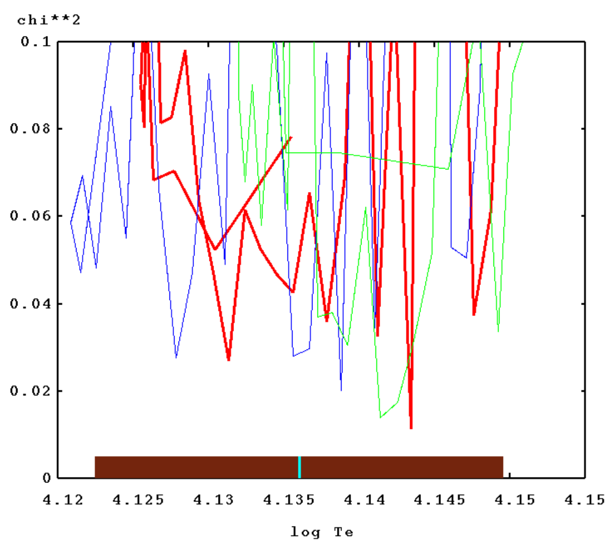
- T_e = 13700 ± 500 K
- *log g* = 3.79 ± 0.14 (Aerts et al. 2006)

HD163830

Our calculations:

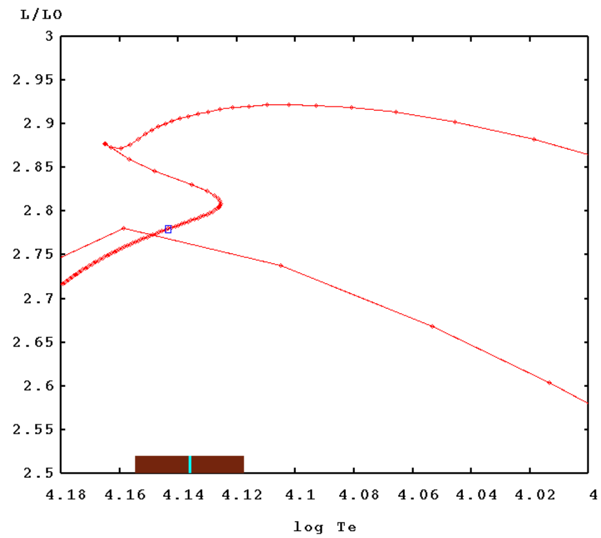
- **Calibration COROT/MOST ←→ CESAM+ROMOSC/CLES+MAD**
  - **18 observed modes M** (*g*, *l*=0-2);
  - χ^2 minima for a grid of tracks:
    - M = 4.0 $M_\odot$ - 5.0 $M_\odot$; grid step 0.005 $M_\odot$;
    - Z = 0.01, 0.02, 0.03;
  - range of effective temperature: 13700 ± 500K;

HD163830



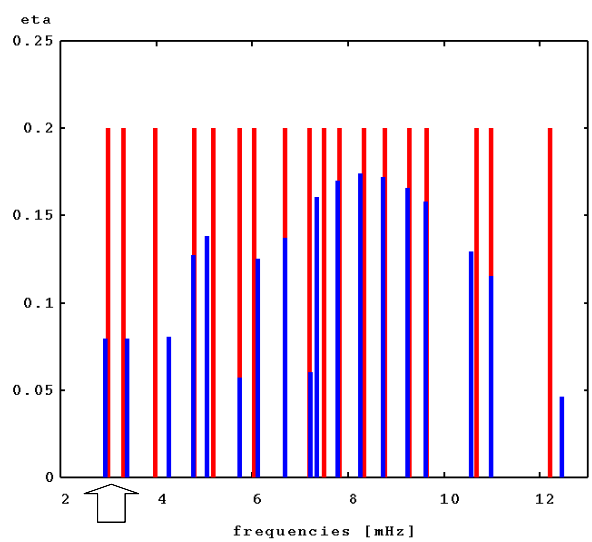
The minima of the $\chi 2$ as function of log(Te), calculated using the observed modes for the star HD163830(M, Aerts,2006). The evolutionary postms tracks are for a stars of 4.5 M⊙ , Z = 0.02, (red) , 4.4 M⊙ , Z = 0.02, (green) , 4.4 M⊙ , Z = 0.02, (blue) . In brown is indicated the observed zone in temperature for the star: 13700 ± 500 K.

HD163830



Evolutionary tracks in the HR diagram for a star of 4.4 M⊙ , Z = 0.02 star in diagram HR. Also, in the diagram the position of the star HD 163830 is indicated.

HD163830



The spectra of the observed modes for the star HD 163830 (18 modes M; in red) compared with the theoretical one (η in blue) for a star of 4.50 M⊙ Z=0.02.

HD163830

Parameter	Bucharest Min I	Bucharest Min II	Bucharest Min III
χ^2	0.0114	0.0174	0.0201
$M/M_\odot$	4.5	4.6	4.4
Z	0.02	0.02	0.02
T_e (K)	13912.	13894.	13767.
log $(L/L_\odot)$	8.77	8.82	8.82
$R/R_\odot$	2.78	2.84	2.40
t (Gyr)	2.35	2.40	2.41

V351 Ori

- pms/postms type?

V351 Ori

- **V351 Ori: A7 III, V=8.9, d>210 pc, v_r =16.9km/s, vsin(*i*)=87.3km/s, Te=7700±250K [log(Te)=3.88], log(*g*)=1.4.**

- **Evolutionary status of V351 Ori is still debaded in the literature !**

  - strong photometrical variations – **pms like**
    (attributed to extinction by circumstellar dust clouds)
  - presence of Hα emission with strong inverse P Cyg profile - **pms like**
  - SI λ1296 Å and OI λ1304 Å UV lines - **pms like**
  - broad infrared excess - **pms like**

  - lack of a reflection nebula and of association with an obscured region (lack criteria Herbig Ae star) - **postms like**
  - not kinematically linked to Orion star formation region - **postms like**
  - anomalous chemical composition (low H abundance) - **postms like**
  - λ Boo pms or postms type **?**

V351 Ori. Observed pulsational spectra

- **Balona, L. A.; Koen, C.; van Wyk, F.,** 2003, M.N.R.A.S., 333, pp. 923-931 [BKW];

- **Catala, C.,** 2003, Astrophysics and Space Science, pp. 53-60 [C]

- **Marconi, M.; Ripepi, V.; Palla, F**.; **Ruoppo, A**., 2004, Communications in Asteroseismology, 145, pp. 61-66 [M];

- **Ripepi, V.; Marconi, M.; Bernabei, S.; Palla, F.; Pinheiro, F. J. G.; Folha, D. F. M.; Oswalt, T. D.; Terranegra, L.; Arellano Ferro, A.; Jiang, X. J.,** 2003, Astronomy and Astrophysics, v.408, pp.1047-1055 (2003) [RP].

V351 Ori.

Observed pulsational spectra P^{obs} [c/d]

C	RP	M	BKW1	BKW2
11.780		11.890		11.887
	12.754			
	12.817			
13.227				
	14.331		14.333	14.153
15.687	15.687	15.490	15.675	15.686
	15.885			
16.868		16.270		
		26.77		

V351 Ori.

Our calculations:

- **Model I. C;** **track** 1.80 $M_\odot$, CESAM0;

- **Model II. RP;** (*g*, *p*, *l*=0-2), CESAM2k_V2
- χ^2 minima test for a **grid of tracks:**
  - M = 1.70 $M_\odot$ - 2.50 $M_\odot$;
  - Z = 0.01 - 0.04;
- **range of effective temperature:** 7700 ± 70K**.**

V351 Ori
Model I. CESAM0.Suran, Popescu, COROTWEEK 8

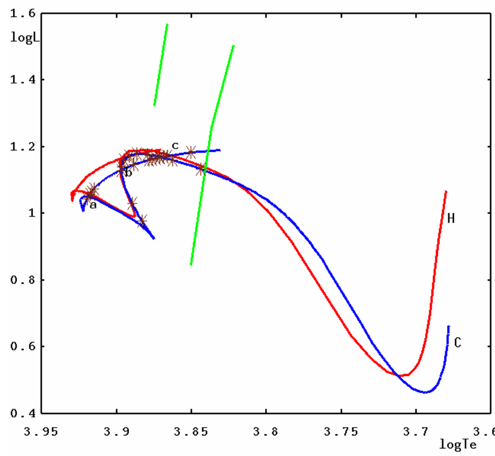


Figure 1. Evolutive tracks of 1.8 $M_\odot$ star in the HR diagram. [CESAM0 vs. HENYEY].
Common points pre/postMS labeled by a,b,c.
In the figure also is indicated the main instability strip.

V351 Ori
Model I. CESAM0.Suran, Popescu, COROTWEEK 8

Common pms and post-ms points on the track of 1.8$M_\odot$ star.

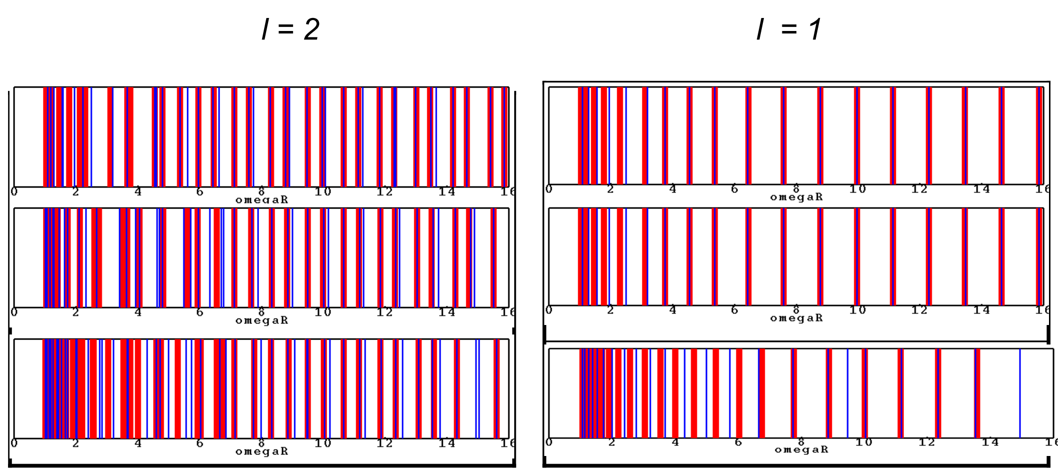
	Log T_e	Log L	R	Age (Myr)	X_c	r_{conv}
[a]:						
M13	3.919	1.050	1.621	11.8	0.7134	0.186
M16	3.920	1.044	1.608	300.	0.6383	0.204
[b]:						
M8	3.897	1.129	1.970	8.25	0.7142	0.221
M19	3.897	1.131	1.978	900.	0.4355	0.191
[c]:						
M4	3.872	1.170	2.319	7.7	0.7142	0.068
M23	3.872	1.167	2.312	1160.	0.3132	0.180

Model I. CESAM0.Suran, Popescu, COROTWEEK 8; 1.8$M_{\odot}$ star

Pulsational spectra for V351 Ori. Theoretical model - common point c.

C	RP	M	BKW1	BKW2	Th.pms	Th.post
11.780		11,890		11.887	11.657 F	11.717 F
	12.754				12.297 1	12.020 1
	12.817					12.131 2
13.227					13.078 2	
	14.331		14.333	14.153		14.122 2
15.687	15.687	15.490	15.675	15.686	15.089 1H	15.167 1H
	15.885				15.584 1	15.522 1
16.868		16.270				16.441 2
		26.77			26.059 4H	26.240 4H

Model I. CESAM0. Suran, Baglin, Goupil, Lebreton; 1.8$M_{\odot}$ star



Pulsational spectra for V351 Ori. Theoretical model - common point c. (last line)

Model I. CESAM0.Suran, Popescu, COROTWEEK 8; 1.8$M_{\odot}$ star

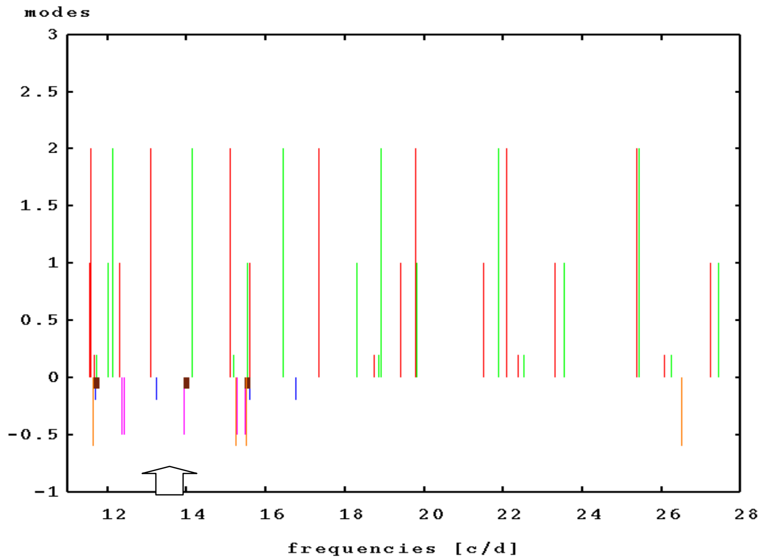
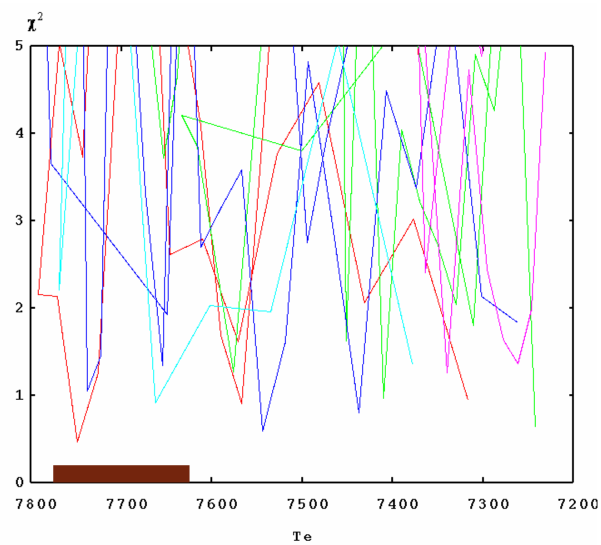


Figure . The observed and theoretical pulsational spectra for the star V351 Ori.
Impulses greater than zero – theoretical spectra: red – pms star; green – postms star (*l* = 0-2) .
Impulses less than zero – observed spectra: magenta – Rippepi; blue – Catala; light brown – Marconi; intense brown –Balona.

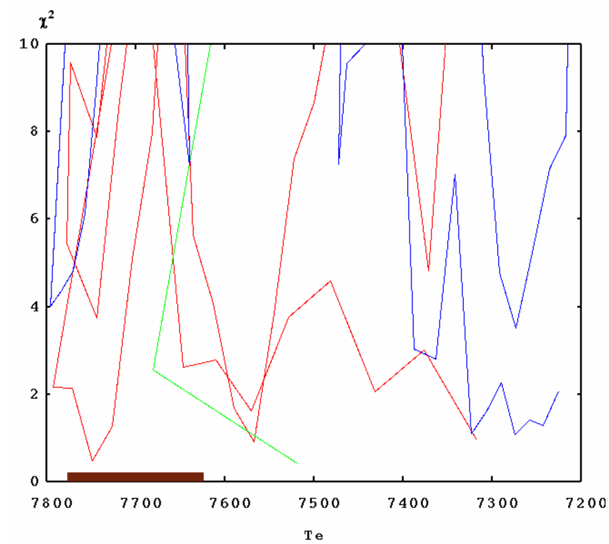
Model II. CESAM2k_V2. Postms model.



CESAM2k_V2 model of V351 Ori for Z=0.02 and masses 1.8$M_{\odot}$ (magenta), 1.9$M_{\odot}$ (green), 2.0$M_{\odot}$ (blue), 2.1$M_{\odot}$ (red), 2.2$M_{\odot}$ (vernil). In brown is shown the observed range of temperature for the star .

➔ The optimal asteroseismological model is 2.1$M_{\odot}$.

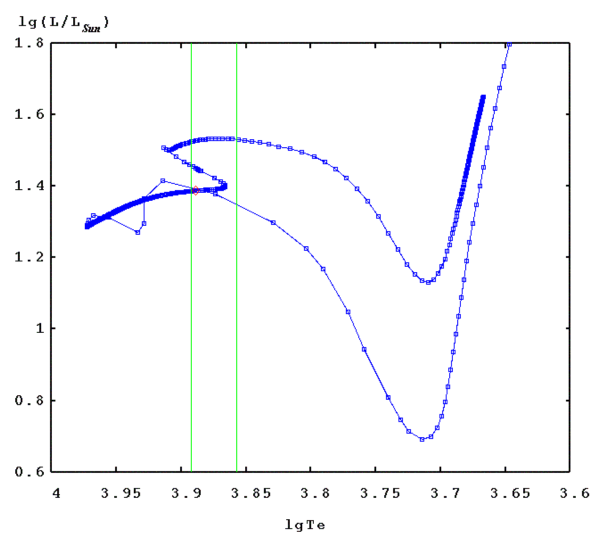
Model II. CESAM2k_V2. Postms model.



CESAM2k_V2 model of V351 Ori for 2.1M$_\odot$ and Z=0.01 (green), 0.02 (red) şi 0.03 (blue).
In brown is shown the observed range of temperature for the star .

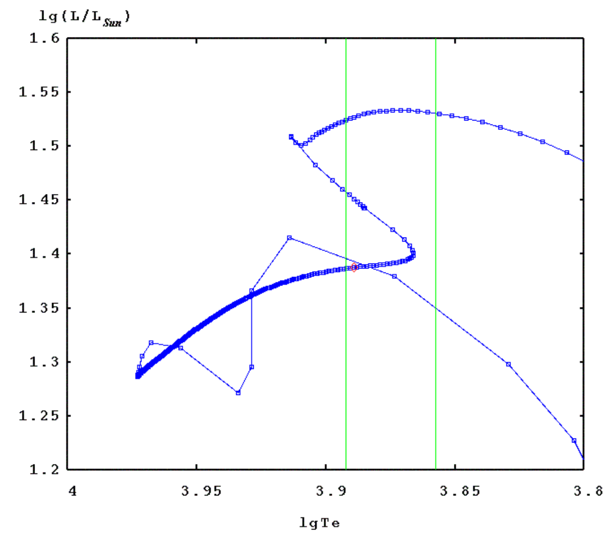
➔ **The optimal asteroseismological model: 2.1M$_\odot$, Z = 0.02 .**

Model II. CESAM2k_V2. Postms model.



Evolutionary track in the HR diagram for the optimum model:
M=2.1M$_\odot$, X=0.71 şi Z=0.02.
In red is indicated the position in the HR diagram for the star V351 Ori.

Model II. CESAM2k_V2. Postms model.



Zoom of the evolutionary track in the HR diagram for the optimum model:
M=2.1M⊙, X=0.71 şi Z=0.02.
In red is indicated the position in the HR diagram for the star V351 Ori.
➔ **the evolutive status of V351 Ori – near to the common point pms/postms.**

V351 Ori. Model II. CESAM2k_V2. Postms model.

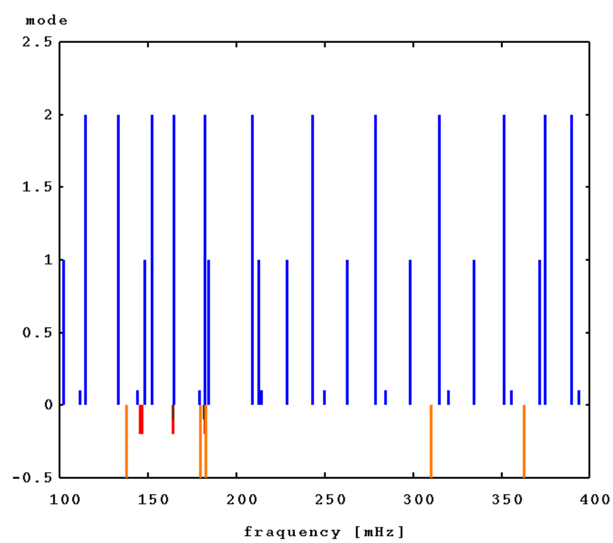


Figure . The observed and theoretical pulsational spectra for the star V351 Ori.
Impulses greater than zero – theoretical spectra: blue (l = 0-2) .
Impulses less than zero – observed spectra: magenta – Rippepi; light brown – Marconi; intense brown –Balona.

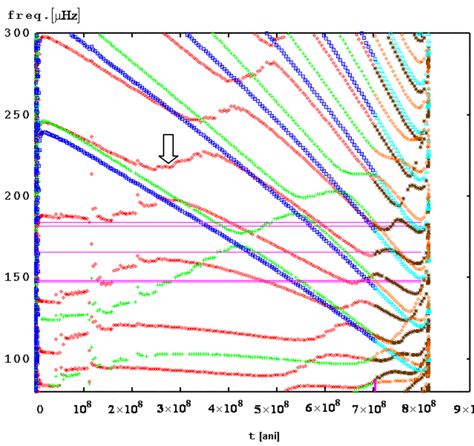
V351 Ori. Model II. CESAM2k_V2. Postms model. Physical elements.

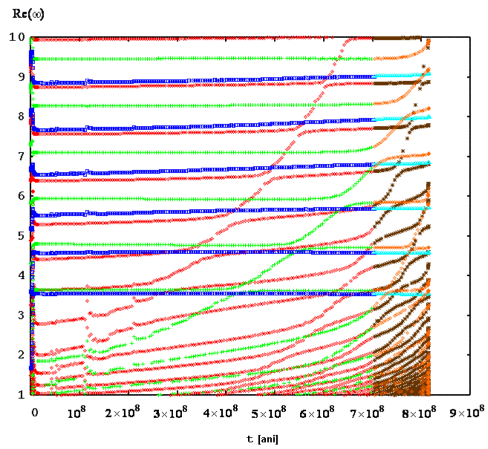
χ^2	0.466
$M/M_{\odot}$	2.1
Z	0.02
T_e	7749 K
$L/L_{\odot}$	24.41
$R/R_{\odot}$	2.77
t(yr)	7.02 10^8

V351 Ori. Model II. CESAM2k_V2. Postms model. Observed and calculated frequencies and the corresponding modes.

	observed frequencies [μHz]	calculated frequencies [μHz]	differences
f_1	147.6157	148.15 (*l=2, n=-1)*	0.5343
f_2	148,3449	148.15 (*l=0,n=2)* *1H*	0.1949
f_3	165.8681	164.52 (*l=2, n=1)*	1.3481
f_4	181.5625	182.00 (*l=2, n=2)*	0.4375
f_5	183.8542	183.88 (*l=0, n=3)* *2H*	0.0258

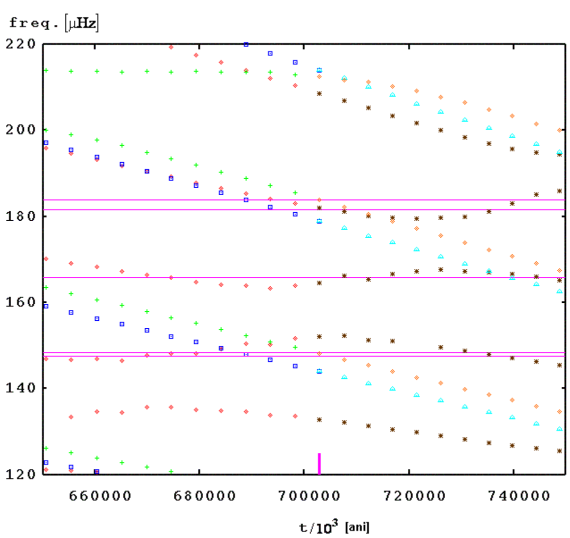
V351 Ori. Model II. CESAM2k_V2. Postms model.





Pulsational evolutive spectra [freq.(μHz), t] and [ω_R , t] for the star V35 .
Also are indicated the observed frequencies, and the evolutionary position of the star. The arrow indicates the observed penetrative mode.

V351 Ori. Model II. CESAM2k_V2. Postms model.



Pulsational evolutive spectra [freq.(μHz), t]   for the star V35 .
Also the observed frequencies and the evolutionary position of the star are indicated..

ROMOSC results

	ROMOSC
• **η Boo** - δ Scuti type	
- excitation mechanism?	- yes. classical?
- M+ground connection?	- high χ^2 ?
• **HD 163830** - B (SPB) type	
- excitability?	- yes. 2 modes more.
- rotation?	- without rotation.
• **V351 Ori** - δ Scuti	
- pms/postms?	- 1 penetrative mode dissemination.