Asteroseismology of $\beta$ Cephei stars: effects of the chemical composition

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Variable MS stars in the HR diagram

about 200 known \( \beta \) Cephei stars

\[ \beta \text{ Cephei} \]

\[ \text{SPB} \]

\[ \text{Solar-like} \]

Instability strip

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Helas II - Göttingen - August 20072
Excitation of modes in B stars

Two major updates/uncertainties:

- **Revised solar metal mixture**
  
  Asplund et al. 2005 A&A

  Fe, Ni \( \rightarrow \) 25%

- **Updated opacities from OP**
  
  Badnell et al. 2005 MNRAS

Miglio et al. 2007 MNRAS 375 L21

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Excitation of modes in B stars

$0 \leq \ell \leq 3$
$Z=0.02$
$\beta$ Cep

$0 \leq \ell \leq 3$
$Z=0.01$
$\beta$ Cep

$\log(L/L_\odot)$ vs $\log(T_{\text{eff}})$

OPAL G93
OP G93
OPAL AGS05+Ne
OP AGS05 + Ne

SPB

Miglio, Montalban, Dupret, 2007 CoAst
Excitation of modes in B stars

- Larger hot wing of opacity bump: Bluer border of SPBs and $\beta$ Cephei instability strip
- Larger number of hybrid SPB-$\beta$ Ceph pulsators
- More $\beta$ Cephei modes excited at $Z=0.01$
- Red border of SPBs instability strip almost unchanged

Miglio, Montalbán, Dupret, 2007 MNRAS

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Pulsations of $\beta$ Cephei stars

- Multiperiodic: a few radial and non-radial pulsation modes of low degree and low order are excited
  \(-\approx\) mechanism in iron-group opacity bump around 10000 degrees
- Sparse spectrum
- Multiplets are resolved and well separated
- Short period pulsators (a few hours)
- $p$, $g$ and mixed modes \(\rightarrow\) info on the internal structure

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Asteroseismology of $\beta$ Cephei stars

• Strategy: Forward modelling
• Parameters: X, Z, $\alpha_{ov}$, M, age
• Try to fit the observed frequencies
• If problems: try to improve the physics
  - different chemical composition
  - different opacities
    - diffusion and radiative accelerations
    - mixing
    - .....
A case study: ν Eri

• Many observed frequencies (latest results: Jerzykiewicz et al 2005)
• Identified modes and multiplets
• Well-studied by several independent groups (Pamyathnykh et al. 2004, Ausseloos et al. 2004)
• Problematic star: no satisfactory solution
**vEri: Observations**

**Observed spectrum of oscillations:**

- $f_1=5.7633\,c/d$, $l=0, m=1$
- $f_2=5.6200\,c/d$, $l=1, m=-1$
- $5.6372\,c/d$, $l=1, m=0$
- $5.6539\,c/d$, $l=1, m=1$
- $f_3=6.2236\,c/d$, $l=1, m=-1$
- $6.2438\,c/d$, $l=1, m=0$
- $6.2629\,c/d$, $l=1, m=1$
- $f_4=7.8982\,c/d$, $l=1, m=-1$
- $7.9138\,c/d$, $l=1, m=0$
- $7.9299\,c/d$, $l=1, m=1$

**+Low-frequency modes:**

- $f_A=0.433\,c/d$
- $f_B=0.614\,c/d$

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**v Eri is both a β Cephei and a SPB star**

**Position in the HR diagram:**

- $\log T_{\text{eff}}=[4.33, 4.38]$
- $\log L=[3.6, 4.18]$

**Metallicity:** [0.0083, 0.0127]

(Morel et al. 2006)
Fitting of the frequencies of νEri

Fitting of 1 frequency: fixes the age (or $X_c$)
Fitting of two frequencies: for each $X$, $\alpha_{ov}$: M-Z relation
Fitting of three frequencies: for each $X$, $\alpha_{ov}$: one M and one Z
Fitting of four frequencies: for each $X$, one $\alpha_{ov}$, one M, and one Z

The solution(s) has to fit in the error box in the HR diagram
and
the observed modes have to be excited
Previous studies of \( \nu \) Eri

- Pamyathnykh et al. 2004: fit 3 frequencies
  - Opal opacities, GN93, Opal eq. of state
  - Solution: \( X=0.70 \) (fixed), \( \alpha_{ov}=0 \) and 0.1 (fixed), \( Z=0.015, M=9.8 \) and 9.2
  - Only 2 excited frequencies (\( l=0 \) p1 and \( l=1 \) g1)
  - Ad-hoc enhancement of iron in excitement region: 4 modes excited
  - Problems remain for the low-frequency high-order g modes

- Ausseloos et al. 2004: fit 4 frequencies
  - Opal opacities, GN93, CEFF eq. of state
  - Solution: \( X=0.70 \) (fixed), \( \alpha_{ov}=0.3 \), \( Z=0.016 \), \( M=7.8 \)
    - BUT: Too cold (outside error box)
    - AND none of the four frequencies is excited
New analysis of \( \nu \) Eri

- We re-analyze \( \nu \) Eri using
  - new abundances (AGS05)
  - Neon from Cunha et al 2006
  - OP opacities

- For 2 values of X:
  - X=0.7211 (solar calibration with the new abundances)
  - X=0.70 (value used in previous studies)
New fitting of ν Eri for X=0.7211

- X=0.7211
- Z=0.021
- $\alpha_{ov}=0.22$
- M=9.1
- Red: $l=0$
- Green: $l=1$
- solution: at an avoided crossing

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New fitting of ν Eri

• \( X=0.7211; Z=0.021; \alpha_{ov}=0.22; M=9.1 \)
  \( Y=0.258 \)

• \( X=0.70; \quad Z=0.022; \alpha_{ov}=0.22; M=8.9 \)
  \( Y=0.278 \)
Fitting of the frequencies of $\nu$Eri

Fitting of four frequencies: for each $X$, one $\alpha_{ov}$, one $M$, and one $Z$ : DONE

The solution(s) has to fit in the error box in the HR diagram and
the observed modes have to be excited
Position of the solutions in the HR diagram

OK!!!
Fitting of the frequencies of $\nu$Eri

Fitting of four frequencies: for each X, one $\alpha_{ov}$, one M, and one Z : DONE

The solution(s) has to fit in the error box in the HR diagram:
DONE : OK!

and
the observed modes have to be excited
Excitation of the modes

- X=0.70 and X=0.7211:
  - $f_1$ (l=0 p1), $f_2$ (l=1 g1), $f_3$ (l=1 p2) are excited;
  - $f_4$ (l=1 p3) not excited
  - low-frequency high order g modes excited in range 0.55-0.91 c/d (obs: 0.43 c/d and 0.61 c/d)
Fitting of the frequencies of $\nu$ Eri

Fitting of four frequencies: for each X, one $\alpha_{ov}$, one M, and one Z: DONE

The solution(s) has to fit in the error box in the HR diagram: DONE: OK!

and

the observed modes have to be excited DONE: almost OK!
Conclusions

• New abundances and OP opacities help solve the problems of vEri.
• Very satisfactory solution is found for ≈ Eri
• BUT some problems remain:
  – Z higher than observed (diffusion?); independent of X!
  – highest frequency mode not excited (Fe accumulation?)
  – range of excited high-order g modes