Examples of seismic modelling

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Abstract

Findings of a few recent asteroseismic studies of the main-sequence pulsating stars, as performed in Wojciech Dziembowski’s group in Warsaw and in Michel Breger’s group in Vienna, are briefly presented and discussed. The selected objects are three hybrid pulsators $\nu$ Eridani, 12 Lacertae and $\gamma$ Pegasi, which show both $\beta$ Cephei and SPB type modes, and the $\delta$ Scuti type star 44 Tauri.

Session: STARS - oscillations and stellar models
Individual Objects: $\nu$ Eri, 12 Lac, $\gamma$ Peg, 44 Tau

Introduction

Main-sequence stars (including the Sun) seem to be ideal objects for the seismic modelling, i.e. for construction - or rather refinement - of the models of individual stars using data on their multiperiodic oscillations. The structure of the MS stars has been understood qualitatively quite well but some details of the structure and some physical processes still need to be explained. These problems have been specified and discussed in a very compact and informative form by Marc-Antoine Dupret in his introductory talk (these Proceedings). By fitting stellar models to observational data on oscillations we can obtain detailed constraints on stellar parameters and on physical processes in interiors.

Most of the results, presented in this contribution, have been discussed more thoroughly by Dziembowski & Pamyatnykh (2008) and by Lenz et al. (2008). However, newest observational data (in particular, for 44 Tau) may change some conclusions of those papers.
Hybrid stars $\nu$ Eri, 12 Lac and $\gamma$ Peg

Hybrid stars are main-sequence pulsating variables which show two different types of oscillations: (i) low-order acoustic and gravity modes of $\beta$ Cephei type with periods of about 3 – 6 hours, and (ii) high-order gravity modes of the SPB type with periods of about 1.5 – 3 days. Theoretically, such a behaviour was predicted for $\ell > 5$ by Dziembowski and Pamyatnykh (1993, see Figs. 5 and 6 there) and later, when using newer opacity data, also for the low-degree oscillations (Pamyatnykh 1999). In the HR diagram, the overlapped region of the $\beta$ Cep and SPB type pulsations is very sensitive to the opacity data (see Figs. 3 and 4 in Pamyatnykh 1999), therefore the modelling of hybrid star pulsations will allow to test the opacity of the stellar matter - for example, to choose between two independent sets of the OPAL and OP data (Iglesias

![Figure 1: Pulsational instability domains in the upper part of the main sequence. In the overlapped region of the $\beta$ Cep type and SPB type oscillations the hybrid pulsations are expected. OP opacity data for $\ Z = 0.015$ and for new solar proportions in the heavy element abundances were used (mixture A04, Asplund et al. 2005). The positions of observed stars were obtained using catalogs of Stankov & Handler (2005, $\beta$ Cep) and De Cat (2007, SPB). Three hybrid stars are marked explicitly.](image-url)
& Rogers 1996 and Seaton 2005, respectively). Theoretical $\beta$ Cep and SPB instability domains and position of three confirmed hybrid stars are shown in Fig. 1. All three stars are very close to the region where hybrid pulsations are expected when using the OP opacities.

Figure 2: Observational frequency spectra of $\nu$ Eri and 12 Lac based on Jerzykiewicz et al. (2005) and Handler et al. (2006) data, respectively. The numbers above frequency bars mark mode degree values, $\ell$, as inferred from multicolour photometry (according to Dziembowski & Pamyatnykh 2008).

Fig. 2 shows the observational frequency spectra of $\nu$ Eri and 12 Lac. High-frequency modes of the $\beta$ Cep type are well resolved, and their degree, $\ell$, and in some cases also azimuthal order, $m$, are determined from photometry and spectroscopy. For very slow rotating star $\nu$ Eri, one radial mode, two $\ell = 1$ triplets (modes $g_1$ and $p_1$) and one more mode ($\ell = 1, p_2, \nu = 7.89$ c/d) are identified. For 12 Lac, one radial mode, two components of a $\ell = 1$ triplet and 5 other $\ell = 1$ and/or $\ell = 2$ modes are identified.

The seismic models of $\nu$ Eri which fit radial and two $\ell = 1, m = 0$ frequencies were constructed for different opacities (OP and OPAL) and different assumptions about the efficiency of the overshooting from the stellar convective core. Ausseloos et al. (2004) constructed seismic models of this star which fit one more mode, $\ell = 1, p_2$ at $\nu = 7.89$ c/d, but it was necessary to assume rather unrealistic chemical composition parameters ($X$ and/or $Z$) and a
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quite effective overshooting. Moreover, they did not consider the low-frequency modes of the SPB type pulsations. We argued that the overshooting from the convective core is ineffective in \( \nu \) Eri (seismic models with overshooting are located outside the observational error box in the HR diagram) but this result critically depends on the \( T_{\text{eff}} \) determination.

![Diagram of normalized growth rate, \( \eta \), as a function of mode frequency for \( \nu \) Eri seismic model constructed both with OPAL and OP opacities (\( \eta > 0 \) for unstable modes). Both models fit the observational error box (\( \log L, \log T_{\text{eff}} \)) in the HR diagram. The frequencies of radial fundamental and two dipole modes (\( \ell = 1 \), modes \( g_1 \) and \( p_1 \)) fit the observed values at 5.763, 5.637 and 6.244 c/d, respectively. The observed frequencies are shown by vertical lines, with their lengths proportional to the mode amplitudes in a logarithmic scale. Note that in the OP case there are unstable low-frequency quadrupole (\( \ell = 2 \)) modes, whereas in the OPAL case all low-frequency modes are stable.

Fig. 3 illustrates the effect of the opacity choice between the OPAL and OP data on the instability of \( \ell = 1 \) and \( \ell = 2 \) modes of \( \nu \) Eri seismic model. The OPAL model was discussed by Pamyatnykh et al. (2004). Using the OP data leads to wider frequency instability range, as it has been demonstrated very clearly for whole \( \beta \) Cep and SPB domains by Miglio et al. (2007). They showed also that the effect of the choice between old and new solar proportions in the heavy element abundances - respectively, GN93 (Grevesse & Noels 1993) and A04 (Asplund et al. 2005) - is significantly smaller than that of the opacity...
choice. Only the model constructed with the OP data is unstable in low-frequency modes (high-order g modes of $\ell = 2$) and can fit the measured frequency at 0.61 c/d. The local $\eta$ maximum for $\ell = 1$ nearly coincides with another measured low frequency at 0.43 c/d, but no instability was found there. There is also a problem of excitation and fitting of the observed peaks at 7.89 c/d, one of them was identified from photometry as an $\ell = 1$ mode (it must be $\ell = 1, p_2$ mode). Zdravkov & Pamyatnykh (these Proceedings) demonstrated that an additional opacity enhancement by approximately 50% around the iron bump at its slightly deeper location may lead to the instability of both high-order g modes and $\ell = 1, p_2$ mode at the observed frequencies.

The two $\ell = 1$ triplets in the $\nu$ Eri frequency spectrum allow to constrain internal rotation rate. In Fig. 4, the rotational splitting kernels (weighting functions in the integral over the local rotational velocity inside the star) for two dipole modes of the seismic $\nu$ Eri model are shown. These kernels determine the sensitivity of different layers to the rotational splitting of the oscillation frequencies, therefore from the measured spacings between components of different multiplets we can obtain information about internal rotation. We showed that in $\nu$ Eri the convective core rotates approximately 5 times faster than the envelope.

In Fig. 5, the observed frequency spectrum of 12 Lac is compared with results for a seismic model which was constructed to fit four dominant peaks at 5.0-5.5 c/d: the radial fundamental mode, two components of $\ell = 1$ triplet and one component of the $\ell = 2$ quintuplet. Most of remaining peaks also have their counterparts among theoretical frequencies. The $\eta(\nu)$ dependence is similar to
that for the \( \nu \) Eri model in Fig. 3. The theoretical frequency range of unstable \( \beta \) Cep type modes fits the observed peaks very well. However, the high-order g modes of \( \ell = 1 \) and \( \ell = 2 \) are stable, in contrast to the \( \ell = 2 \) case of \( \nu \) Eri. Again, the solution of the problem may require an opacity enhancement in the driving zones in deep envelope. From the frequencies of two components of

\[
\begin{align*}
\eta_{\ell=1} & \quad \nu_{\ell=1} \\
\eta_{\ell=2} & \quad \nu_{\ell=2}
\end{align*}
\]

Figure 6: The normalized growth rates of \( \ell = 1 \) and 2 modes in two \( \gamma \) Peg models constructed with the OP opacities for the heavy element mixture A04. Both models have mass of 8.7 \( M_\odot \) but differ in the heavy element mass fraction, \( Z \). Two larger points close to the \( \nu_4 \) mark mode \( \ell = 1, g_1 \).
rotationally splitted $\ell = 1$ triplet (and taking into account a necessity to fit the observed $\ell = 2$ peak at 4.2 c/d) we estimated that the convective core rotates approximately 4.6 times faster than the envelope, this result is similar to that for $\nu$ Eri. The calculated surface equatorial velocity of 47 km/s agrees very well with the spectroscopic estimation of about 50 km/s.

$\gamma$ Peg is also a hybrid star (Chapellier et al. 2006 and private communication by G. Handler) with two oscillation frequencies of the $\beta$ Cep type (6.01 and 6.59 c/d), and two - of the SPB type (0.686 and 0.866 c/d). Fig. 6 illustrates preliminary results of the modelling. The models were constructed by fitting the frequency of the radial fundamental mode to the observed frequency at 6.59 c/d. As it is easy to see from Fig. 6, the frequency of dipole mode $\ell = 1, g_1$ can fit the observed value 6.01 c/d in a model with $Z$ value in between 0.015 and 0.02. Two observed low-frequency modes are well inside the frequency range of unstable high-order gravity modes of $\ell = 2$. The identification of the mode degree for observed peaks will allow to check these preliminary assessments. Now, an intensive campaign of ground-based and cosmic observations (with the MOST satellite) is on the way (G. Handler, private communication).

44 Tau

The $\delta$ Sc t type variable 44 Tau is an extremely slowly rotating star in which 15 oscillation frequencies have been measured (Antoci et al. 2007, Breger & Lenz 2008). Two of them are identified as radial modes. Moreover, 7 other...
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modes have been identified as $\ell = 1$ and $\ell = 2$ oscillations. The $\log g$ value as determined from photometry and spectroscopy does not allow to choose between the main-sequence and post-MS model for this star. Lenz et al. (2008) gave asteroseismic arguments in favor of the post-MS model. In particular, only post-MS model can fit both observational error box in the HR diagram and frequencies of two radial modes. In Fig. 7 the observed and theoretical frequency ranges are compared for two 44 Tau star models. In contrast to a similar plot given by Lenz et al. (2008), this figure also includes the previously unknown lowest frequency mode at 5.30 c/d which has been detected very recently (Breger & Lenz 2008). This finding may be an argument against the post-MS models for 44 Tau which have no unstable modes at these low frequencies.

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DISCUSSION

Arlette Noels: I fully agree with you that there probably is a missing opacity not only in \( \beta \) Cep stars but all along the MS. I am however surprised by your results for \( \nu \) Eri on the comparison between OP and OPAL opacities. The “best” models you obtain are very different which means that the change is not only due to changes in the iron bump but also to changes in the whole star. Do you agree with that? This is very different from an increase of opacity limited to the iron bump which will only affect the excitation of the modes.

Alexey Pamyatnykh: You are correct in that our best seismic models computed with the OPAL and OP data differ in a some extent not only in the iron bump region but also in the whole star. The most important difference between the OP and OPAL opacities is that in the OP case the iron bump is located slightly deeper in the star (at slightly higher temperatures) compared with the OPAL case. Our seismic models of \( \nu \) Eri fit the observed frequencies of the radial fundamental mode and two dipole modes \((g_1, p_1)\) very nicely, with an accuracy better than \(10^{-3}\). The opacity changes around the iron bump even by about 20 percent (which is a systematic difference between OP and OPAL at fixed temperature in this region) lead to a change of the stellar structure and consequently to a change of the oscillation frequency spectrum, so to fit the observed frequencies we must adjust global stellar parameters - such as mass, heavy element abundance and effective temperature. Therefore, the structure of the seismic model constructed with the OP data will differ in a some extent from that of the model constructed with OPAL.

Again, an additional similar opacity change around the iron bump will also affect the oscillation frequencies (not only the mode excitation) and thereby the corresponding seismic model. Such a test with artificially enhanced opacity in a vicinity of the iron bump (more exactly, slightly deeper than the iron bump!) has been performed by T. Zdravkov and myself (these Proceedings).