A complex asteroseismic study of the hybrid B-type pulsator $\nu$ Eridani

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Abstract We present results of comprehensive seismic modelling of the B-type main-sequence pulsator $\nu$ Eridani, which consists in parallel fitting of the pulsational frequencies and corresponding values of the complex, nonadiabatic parameter $f$, defined by the bolometric flux perturbation. This kind of studies, which we call complex asteroseismology, provides a unique test of stellar opacities. Our results indicate a preference for the OPAL data.

Keywords stars: early-type, oscillations, $\nu$ Eridani

1 Introduction

$\nu$ Eridani (HD 29248) is a well known $\beta$ Cep/SPB type pulsator with the B2III spectral type and brightness of $m_V = 3.92$ mag. The star is a slow rotator with the velocity of about 6 km/s derived from a rotational splitting of pulsational frequencies. In the last years, this variable has attracted a lot of interest thanks to dedicated photometric (Handler et al. 2004, Jerzykiewicz et al. 2005) and spectroscopic (Aert et al. 2004) multisite campaigns. The frequency analysis revealed 14 independent peaks in photometry (Handler 2004, Jerzykiewicz et al. 2005) and 9 of them were identified also in spectroscopy (Aerts et al. 2004, de Ridder et al. 2004). Subsequently, several papers were devoted to seismic analysis of $\nu$ Eri. Pamyatnykh, Handler & Dziembowski (2004) presented the first seismic modelling of this star with a special emphasis of excitation problem for high-order g mode. Ausseloos et al. (2004) managed to fit four frequencies but for models with very low effective temperature (far outside the 3$\sigma$ error) or unacceptable chemical composition. Daszyńska-Daszkiewicz et al. (2005) undertook the first attempt to compare the empirical and theoretical values of $f$ for the radial mode, but neither with OP nor with OPAL opacity tables an agreement was achieved. More recently, Dziembowski & Pamyatnykh (2008) redid seismic modelling with the new solar chemical composition as determined by Asplund et al. (2004, hereafter A04) but again no satisfactory interpretation of the whole $\nu$ Eri spectrum was obtained. Effects of differential rotation in the analysis of rotational splitting of three $\ell = 1$ modes and their asymmetries were included by Suarez et al. (2009). A few years ago, the asymmetry of one $\ell = 1$ triplet was suggested to be caused by a strong magnetic field (Dziembowski & Jerzykiewicz 2003), but its presence was not confirmed (Schnerr et al. 2006).

A position of $\nu$ Eri in the HR diagram is shown in the right panel of Fig. 1. The observational values of the effective temperature and luminosity were taken from Pamyatnykh, Handler & Dziembowski (2004). The evolutionary tracks, shown from ZAMS to TAMS, were computed with the Warsaw-New Jersey evolutionary code adopting the OP opacities and the A04 solar mixture. We assumed the rotational velocity of 10 km/s and hydrogen abundance of $X = 0.7$ at ZAMS. The effect of the heavy elements abundance, $Z$, and the overshooting parameter, $\alpha_{ov}$, on the evolutionary tracks is also presented. Other features of this figure will be discussed later on.

Here, we present mode identification for all detected pulsational frequencies as well as one more attempt towards seismic modelling of this B-type hybrid pulsator. In our studies we aim at simultaneous fitting of the pulsational frequencies and corresponding values of the complex, nonadiabatic parameter $f$, taking into account instability conditions. All pulsation computations were done using the linear nonadiabatic
code of Dziembowski (1977). The $f$-parameter is the complex photospheric amplitude of the radiative flux perturbation and, in the case of B-type pulsators, its value is very sensitive to metal abundance and opacities (Daszyńska-Daszkiewicz et al. 2005). Such extended seismic study has been recently done for the β Cep star θ Ophiuchi (Daszyńska-Daszkiewicz & Walczak 2009). In these proceedings we give only a very brief outline of our results. The full analysis will be published elsewhere.

2 Mode identification

Although a few years have elapsed since the second photometric campaign of ν Eri (Jerzykiewicz et al. 2005), mode identification employing photometric observables for all 14 pulsational frequencies has never been undertaken. The $w_{\nu}$ Strömgren photometry and radial velocity measurements allowed us to apply two approaches to identify the mode degree, $\ell$. In the first case, we compare observational values of the amplitude ratios and phase differences between available passbands with their theoretical counterparts and rely on theoretical values of the $f$-parameter, which results from linear nonadiabatic computations of stellar oscillations (Cugier, Dziembowski & Pamyatnykh, 1994). In the second method, one makes use of amplitudes and phases themselves and the value of $f$ is determined simultaneously with $\ell$ in the Least Square process (Daszyńska-Daszkiewicz et al. 2003, 2005). In the case of B-type pulsators, the second method demands adding the radial velocity measurements to get an unambiguous identification of the degree, $\ell$. In both methods we adopt the Kurucz models of stellar atmospheres.

In Tab. 1 we give identification of $\ell$ for all pulsational frequencies of ν Eri from two approaches; $\ell_1$ and $\ell_2$ correspond to determination with the theoretical and empirical values of $f$, respectively. Next columns contain values of the amplitudes and phases in the Strömgren $y$ passband and of radial velocity variation. As we have mentioned above, from the second method we derive also the complex parameter $f$, whose exemplary values are given in the last two columns of Tab. 1. The empirical values of $f$ can be compared with the results of the nonadiabatic pulsation computations. In the next section, a requirement of getting an agreement for the $f$-parameter will be added to seismic modelling.

3 Seismic models of ν Eridani

In the left panel of Fig. 1, we put seismic models of ν Eridani on the $Z$ vs. $\alpha_{\nu}$ plane. All these models reproduce three centroid frequencies: $\nu_1(\ell = 0, p_1)$, $\nu_4(\ell = 1, g_1)$ and $\nu_6(\ell = 1, p_1)$, and were found with the OP and OPAL tables assuming the A04 solar composition. Models to the left of the vertical thick dash line have all these three modes unstable. Moreover, in this family of seismic models there are ones which fit also the fourth centroid frequency, $\nu_9(\ell = 1, p_2)$ (big dots in Fig. 1), but with a worse accuracy and this mode is stable. These models are beyond the observational error box but still within the $3\sigma$ error of the effective temperature. A similar result was obtained by Ausseloos et al.
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(2004) but for cooler temperatures or rather unrealistic chemical composition.

The results obtained with the OP and OPAL opacity tables are similar but the OPAL seismic models require smaller metallicity, have larger masses and effective temperatures which fit better observational values of the effective temperature, $T_{\text{eff}}$, and luminosity, $L$ (see the right panel of Fig. 1).

For a comparison of the empirical and theoretical values of the $f$-parameter, we chose two seismic models within the observational error box computed with the OP and OPAL tables (star symbols in Fig. 1). In Fig. 2, we show this comparison for nine frequencies found in both photometry and spectroscopy. As can be seen, there is an agreement for the most pulsational frequencies including the SPB-type mode, $\nu_B=0.6144$ c/d. The discrepancy for the remaining frequencies is related to a low accuracy in amplitudes and phases. In Fig. 3, we present a more detailed comparison for the radial mode, $\nu_1$, using all OP and OPAL seismic models. As we can see, an agreement can be achieved only with the OPAL data and for cooler models.

4 Conclusions

We presented mode identification for all 14 pulsational frequencies detected in the light variation of ν Eri. For nine frequencies, visible also in the radial velocity variation, we were able to apply the method of simultaneous determination of the mode degree, $\ell$, and the complex, nonadiabatic parameter $f$. In the next step, we looked for stellar models which fit three centroid frequencies: $\nu_1$, $\nu_4$ and $\nu_6$. Using opacities from both the OP and OPAL tables and the A04 chemical mixture, we found a family of seismic models with different masses, temperatures, metallicities and core overshooting parameters. Seismic models computed with the OPAL opacities fit better observational values of $T_{\text{eff}}$ and $L$. We managed to find also models which fit the fourth centroid frequency, $\nu_9$. The accuracy of this fitting is worse comparing to the first three frequencies but these models are within the $3\sigma$ error of $T_{\text{eff}}$.

Then, we compared the empirical and theoretical values of the $f$-parameter for nine frequencies which appeared in both photometry and spectroscopy. The overall agreement is very encouraging. In particular, the obtained concordance for high-order g mode opens a new gate in seismic studies of the hybrid pulsators of the $\beta$ Cep/SPB type. Moreover, a detailed comparison of the values of $f$ for the radial fundamental mode showed that the OPAL tables are clearly favoured. The same result was obtained by Daszyńska-Daszkiewicz & Walczak (2009) from the analysis of the $\beta$ Cep star $\theta$ Ophiuchi.
Fig. 2 Comparison of the empirical and theoretical values of $f$ in the whole range of frequencies observed in both photometric and spectroscopic variation of $\nu$ Eri. The real and imaginary parts of $f$ are plotted in the left and right panel, respectively. Theoretical values of $f$ correspond to the OP and OPAL seismic models marked with star symbols in Fig. 1. Modes with the degree, $\ell$, from 0 to 4 were considered.

Fig. 3 Comparison of the empirical values of $f$ for the radial fundamental mode, $\nu_1$, with theoretical ones corresponding to the OP and OPAL seismic models of $\nu$ Eri.

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