Complex asteroseismology of the hybrid B-type pulsator $\gamma$ Pegasi: a test of stellar opacities

P. Walczak* and J. Daszyńska-Daszkiewicz**

Instytut Astronomiczny, Uniwersytet Wrocławski, ul. Kopernika 11, 51-622 Wrocław, Poland

The dates of receipt and acceptance should be inserted later

Key words stars: early-type - stars: oscillations - stars: individual: $\gamma$ Pegasi - atomic data: opacities

Using the updated oscillation spectrum of $\gamma$ Pegasi, we construct a set of seismic models which reproduce two pulsational frequencies corresponding to the $\ell = 0$, $p_1$ and $\ell = 1$, $g_1$ modes. Then, we single out models which reproduce other well identified modes. Finally, we extend our seismic modelling by a requirement of fitting also values of the complex, nonadiabatic parameter $f$ associated to each mode frequency. Such complex asteroseismology of the B-type pulsators provides a unique test of stellar metallicity and opacities. In contrast to our previous studies, results for $\gamma$ Peg indicate that both opacity tables, OPAL and OP, are equally preferred.

© WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

1 Introduction

Oscillation spectra of the main sequence B-type pulsators are characterized by a low number of frequency peaks and a lack of distinct regularities. Despite of these facts, asteroseismology of these massive stars provides valuable constraints on stellar physics and evolution.

Last years, the most attractive targets for asteroseismic studies have become hybrid pulsators which exhibit low order $p/g$ modes as well as high-order $g$-modes. This is because these two types of modes sound various parts of the stellar interior. In the case of the early B-type stars, modes typical for the $\beta$ Cep and SPB type occur simultaneously. The analysis of extensive observations, especially from multisite campaigns, allowed to discover several pulsating variables of the $\beta$ Cep/SPB type.

The first detected hybrid pulsator of the early B spectral type was $\nu$ Eridani (Aerts et al. 2004; Handler et al. 2004; Jerzykiewicz et al. 2005). The next example is 12 Lacertae (Desmet et al. 2009; Handler et al. 2006). Many excellent papers devoted to seismic modeling of these stars have been published, but a limited space of this article does not allow to mention them.

$\gamma$ Pegasi is one more hybrid pulsator of early B spectral type. Recent analysis of the space based observations from the MOST satellite (Handler et al. 2009) led to discovery of 14 pulsational frequencies with 8 of the $\beta$ Cep type and 6 of the SPB type.

Asteroseismic modeling, consisting in fitting theoretical and observational values of pulsational frequencies, can be extended by adding another seismic tool associated to each mode frequency. Such a tool is the amplitude of the bolometric flux perturbation to the radial displacement, called the $f$-parameter. This seismic probe was introduced by Daszyńska-Daszkiewicz, Dziembowski & Pamyatnykh (2003, 2005). Theoretical values of $f$ are obtained from pulsation computations and their empirical counterparts are derived from multicolour photometry. The parallel fitting of pulsational frequencies and corresponding values of the $f$-parameter was termed complex asteroseismology by Daszyńska-Daszkiewicz & Walczak (2009). The hybrid pulsators are of particular interest because the dependence of $f$ on pulsational frequency, $\nu$, and the mode degree, $\ell$, is completely different for $p$ modes and high-order $g$-modes.

Complex seismic modeling has been applied to the $\beta$ Cep star $\theta$ Oph (Daszyńska-Daszkiewicz & Walczak 2009) and to $\nu$ Eri (Daszyńska-Daszkiewicz & Walczak 2010). In the case of $\theta$ Oph, we got a strong preference for the OPAL data. From the $\nu$ Eri analysis a contradictory result was obtained: the $\beta$ Cep-type modes indicate the OPAL opacities whereas the SPB-type modes prefer the OP data.

In this paper we present complex seismic modeling of $\gamma$ Peg. In Section 2, we give a short description of the star. Section 3 is devoted to mode identification for all detected pulsational frequencies. Results of our seismic modeling are presented in Sections 4. Conclusions end the paper.

2 $\gamma$ Pegasi

$\gamma$ Peg (HD 886) is a bright star (V=2.83 mag) of the B2IV spectral type. Its low amplitude variability was discovered almost a century ago from the radial velocity observations (Burns 1911). These changes were confirmed by McNamara (1953) who classified $\gamma$ Peg as the $\beta$ Cephei pulsating variable.

© WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim
For dozens of years, γ Peg has been thought to be a monoperiodic star, pulsating in the radial mode with the period of about 0.15175 d [Jerzykiewicz 1970]. Finally, Chapellier et al. (2006) reported discovery of three additional pulsational frequencies; one in the β Cep range and two in the SPB frequency domain. Chapellier et al. (2006) claimed also that this star is a spectroscopic binary with the orbital period of 370.5 d. However, on the basis of space observations from the MOST mission and the ground based photometry and spectroscopy [Handler et al. 2009] and Handler (2009) showed that γ Peg is a single star and the hypothetical orbital variations can be explained by the high-order g-mode pulsation.

In Fig. 1 we show a position of γ Peg in the HR diagram. We included the whole range of the effective temperature, $T_{\text{eff}}$, available in the literature (e.g. Daszyńska-Daszkiewicz & Niemczura 2005 [Handler 2009], Huang & Gies 2008; Morel et al. 2006) and the luminosity was calculated from the Hipparcos parallax and the bolometric correction from models of Kurucz (2004). The evolutionary tracks were computed with the Warsaw-New Jersey evolutionary code adopting the OPAL opacities [Iglesias & Rogers 1996] and the newest heavy element mixture by Asplund et al. (2009), hereafter AGSS09. Only evolution on main sequence is shown. The star is a slow rotator with $V_{\text{rot}} \sin i \approx 0$ as determined from the SiIII lines by Telting et al. (2006). The rotational splitting from the possible two components of the $\ell = 1$ triplet gave $V_{\text{rot}} \approx 3$ km/s [Handler et al. 2009]. Metallicity of γ Peg is smaller than the solar value. Morel et al. (2006) determined $Z = 0.009 \pm 0.002$ from the optical spectra, whereas Daszyńska-Daszkiewicz & Niemczura (2005) obtained $[m/H] = -0.04 \pm 0.08$ (equivalent to $Z = 0.018 \pm 0.003$) from the IUE ultraviolet spectra. The evolutionary tracks in Fig. 1 were computed at the assumption of the equatorial rotational velocity of 3 km/s, hydrogen abundance of $X = 0.7$, two values of metallicity parameter $Z = 0.010$ and 0.015 and no overshooting from a convective core, $\alpha_{\text{ov}} = 0.0$. Lines labeled as $n = 1$ and $n = 2$ will be discussed later on.

3 Identification of the mode degree, $\ell$

To determine the mode degree, $\ell$, of the observed frequencies of γ Peg, we made use of the light variations in the Strömgren $uvy$ passbands [Handler 2009] and the radial velocity changes (Handler et al. 2009). To this aim we applied three approaches.

In the first case, we compared theoretical and observational values of the amplitude ratios and phase differences between the available passbands and relied on the theoretical values of the $f$-parameter. The second approach includes also the radial velocity variation. In the third method we used amplitudes and phases themselves and the $f$-parameter was determined from the observations together with the mode degree, $\ell$.

![Fig. 1](image-url)
Fig. 3  The overshooting parameter, $\alpha_{ov}$, as a function of metallicity, $Z$, for the seismic models of $\gamma$ Peg found from the fitting of the $\nu_1$ frequency (the $\ell = 0$, $p_1$ mode) and the $\nu_2$ frequency (the $\ell = 1$, $g_1$ mode) for hydrogen abundance $X = 0.7$, the OPAL (left panel) and OP opacities (right panel). Hatched areas indicates models fitting $f$-parameter for $\nu_1$ and $\nu_5$.

Table 1  The most probable identification of $\ell$ for the pulsational frequencies of $\gamma$ Peg from three approaches.

| $\nu$  | $\ell$ | $\nu$  | $\ell$ | $\nu$  | $\ell$ |
|--------|--------|--------|--------|--------|--------|
| $\nu_1$ | $0.58974$ | 0 | $0.63551$ | 2 | $0.68241$ | 1 |
| $\nu_2$ | $0.73940$ | 2 | $0.81616$ | 1 | $0.88550$ | 2 |
| $\nu_3$ | $0.91442$ | 3 | $0.95150$ | 4 | $0.81861$ | 0 |
| $\nu_4$ | $1.0352$ | 2 | $1.0823$ | 3 | $0.8552$ | 4 |

4 Complex asteroseismology

To compute pulsational models, we used the linear nonadiabatic code of Dziembowski (1977). We started our seismic modeling by fitting two $p$-mode frequencies: $\nu_1 = 0.58974$ c/d and $\nu_2 = 0.601616$ c/d. A survey of pulsational models showed that if $\nu_1$ is the radial fundamental mode, then $\nu_2$, identified as $\ell = 1$, can be only $g_1$. Here, we assumed that the azimuthal number of $\nu_2$ is $m = 0$. In all computations, we assumed the rotation velocity of $V_{rot} = 3$ km/s and adopted the latest determination of the chemical composition AGSS09. In the left panel of Fig. 3, we present our seismic models fitting $\nu_1$ and $\nu_2$ on the $\alpha_{ov}$ vs. $Z$ plane for the hydrogen abundance of $X = 0.7$ and the OPAL opacities. We depicted the instability borders with the thick solid line for the radial mode, $\nu_1$, and with the thick dashed line for the dipole mode, $\nu_5$. Models that are located below the $\nu = 0$ lines are unstable. We plotted also the lines of constant masses and effective temperatures. Results for the OP tables (Seaton 2008) are quite similar, as can be seen in the right panel of Fig. 3. In both panels, we marked also models which reproduce, within the observational errors, the empirical values of $f$ (hatched areas) of the radial fundamental mode (labeled as $\nu_1$) and of the dipole mode $g_1$ (labeled as $\nu_5$). The region covering models fitting the $f$-parameter corresponding to $\nu_5$ is quite large because of larger observational errors in amplitudes and phases. Unfortunately, there is no model fitting the $f$-parameter for $\nu_1$ and $\nu_5$ simultaneously, regardless of which opacity tables are used. Changing hydrogen abundance did not help in achieving an agreement.

Let us now consider other well identified modes: $\nu_2$, $\nu_4$, $\nu_6$, $\nu_{11}$ and $\nu_{14}$. If we assume that these modes are axisymmetric ($m = 0$), then we can search for pulsational models reproducing additionally one of these five frequencies. In the case of high-order g-modes ($\nu_2$, $\nu_4$, $\nu_6$, $\nu_{11}$), we had to include more than one radial order. In the considered range of the metallicity and overshooting parameter, the $\nu_2$ frequency is $\ell = 2$, $g_{22}$, $g_{23}$ or $g_{24}$ mode. The $\nu_4$ frequency is the $\ell = 2$, $g_{19}$ or $g_{20}$ mode and $\nu_6$ can be the $\ell = 2$, $g_{16}$ or $g_{17}$ mode. We depicted also the $\ell = 1$, $g_9$ mode corresponding to $\nu_{11}$, and the $\ell = 6$, $g_2$ mode corresponding to $\nu_{14}$. Results are presented in Fig. 4. As we can see, models reproducing $\nu_{11}$ cross the hatched areas described above. This means that there are models fitting three frequencies: $\nu_1$, $\nu_5$, $\nu_{11}$ and the $f$-parameter for the radial fundamental or dipole $g_1$ mode. Lines of the $\nu_2$ and $\nu_6$ modes run through the hatched region of $\nu_5$.

Although we managed to derive the empirical values of the $f$-parameter for the high-order g-modes, we could not find models reproducing simultaneously the real and imagi-
binary part of $f$ for any of the SPB-type mode, neither with the OPAL nor OP opacities.

5 Conclusions

The aim of this paper was to construct seismic models of $\gamma$ Peg which reproduce both pulsational frequencies and corresponding values of the nonadiabatic complex parameter $f$. Although we did not fully succeed, we have showed directions and problems that need to be solved.

The first problem we encountered, was that there was no seismic model reproducing simultaneously the $f$-parameter of the radial ($f_1$) and dipole ($f_2$) modes. Secondly, there was no seismic model fitting empirical values of the $f$-parameter for any high-order g-mode.

These inconsistencies can be caused either by the underestimated errors or/and indicate that some additional effects should be included in pulsation modeling. One obvious solution could be inadequacies in the opacity data. Recently, Zdravkov & Pamyatnykh (2009) have suggested increasing opacity by 20-50% around the Z-bump and DOB (Deep Opacity Bump) to explain the observed frequency range of $\gamma$ Peg. Our further studies will show whether this can help also to solve problems reported in this paper.

Acknowledgements. We gratefully thank Gerald Handler for kindly providing data on photometric and radial velocity variations. This work was supported by the HELAS EU Network, FP6, No. 026138 and the Polish MNiSW grant N N203 379636.

References

Aerts C., de Cat P., Handler G., et al.: 2004, MNRAS 347, 463
Asplund M., Grevesse N., Sauval A.J., Scott P.: 2009, ARA&A 47, 481
Burns, K.: 1911, LicOB 6, 141
Chapellier, E., Le Contel, D., Le Contel, J.M., Mathias, P., Valtier, J.-C.: 2006, A&A 448, 697
Daszyńska-Daszkiewicz J., Dziembowski, W.A., Pamyatnykh, A.A.: 2003, A&A 407, 999
Daszyńska-Daszkiewicz J., Dziembowski, W.A., Pamyatnykh, A.A.: 2005, A&A 441, 641
Medupe, R., Mokgwetsi, T., Tlhagwane, P., Rodríguez, E.: 2005, A&A 433, 431
Daszyńska-Daszkiewicz J., Walczak, P.: 2009, MNRAS 398, 1961
Daszyńska-Daszkiewicz J., Walczak, P.: 2010, MNRAS 403, 496
Desmet, M., Briquet, M., Thoula, A. et al.: 2009, MNRAS 396, 1460
Jerzykiewicz, M.: 1970, AcA 20, 93
Jerzykiewicz, M., Handler, G., Rodrigue, M. et al.: 2006, MNRAS 365, 327
Kurucz R.L.: 2004, http://kurucz.harvard.edu
McNamara, D.H.: 1953, PASP 65, 144
Morel, T., Butler, K., Aerts, C., Neiner, C., Briquet, M.: 2006, A&A 457, 651
Seaton, M.J.: 2005, MNRAS 362, 1
Telting, J.H., Schrijvers, C., Ilyin, I.V., Uytterhoeven, K., De Rider, J., Aerts, C., Henrichs, H.F.: 2006, A&A 452, 945
Zdravkov, T., Pamyatnykh, A.A.: 2009, in Stellar Pulsation: Challenges for Theory and Observation, AIP Conf. Proc., eds. J. A. Guzik & P. A. Bradley, Vol. 1170, 388