

Deciphering the period spacing pattern in the oscillation spectrum of the SPB star KIC 7760680

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Abstract. We present the analysis of KIC 7760680, the rotating Slowly Pulsating B-type star identified in the Kepler photometry. The oscillation spectrum of the star exhibits a series of 36 frequencies which are quasi-equally spaced in period. We confirm that this series can be associated with prograde dipole modes of consecutive radial orders. In our studies, the effects of rotation were included in the MESA equilibrium models as well as in the pulsational calculations in the framework of the traditional approximation. We find that pulsational models computed with the OPLIB opacities best reproduce the observed frequency range. The modified opacity data with an enhancement of the opacity at $\log T = 5.3, 5.46$ and 5.06 were tested as well. Increasing the OPLIB opacities by about 50% at $\log T = 5.3$ is sufficient to excite modes in the whole range of 36 frequency peaks of KIC 7760680.

1 Introduction

KIC 7760680 was classified as the Slowly Pulsating B-type star by Pápics et al. [1] who found a series of 36 frequencies quasi-equally spaced in period from the Kepler photometry. From spectroscopic observations the authors derived the effective temperature, $T_{\text{eff}} = 11650 \pm 210$ K, surface gravity, $\log g = 3.97 \pm 0.08$, metallicity, $[M/H] = 0.14 \pm 0.09$ (which corresponds to about $Z = 0.017$) and the minimum value of the rotational velocity, $V_{\text{rot}} \sin i = 61.5 \pm 5$ km s⁻¹. Based on the zero-rotation asymptotic theory, Pápics et al. [1] attributed these frequencies to the prograde dipole gravity modes of high consecutive radial orders. Recently, Moravveji et al. [2] made a detailed seismic modelling of the star taking into account effects of rotation in the framework of the traditional approximation [e. g., 3–9] applied to the non-rotating MESA [10–12] evolutionary models. The authors found that KIC 7760680 is a moderately rotating star with the rotational frequency amounting to 26% of its Roche break up frequency (0.4805 d⁻¹) and with a mass $\sim 3.25M_{\odot}$. Furthermore, they constrained the exponentially decaying convective core overshooting parameter to $f_{\text{ov}} \approx 0.024 \pm 0.001$. Additionally, their best seismic models employed extra diffusive mixing in the radiative envelope. Here, we repeat the Moravveji et al. [2] approach but our computations include the effects of rotation also in equilibrium models. In Sect. 2 we present results of our seismic modelling and conclusions ends the paper.

2 Seismic modelling

Knowledge of the geometry of pulsational modes is essential in seismic modelling. In the case of KIC 7760680, the quasi-equally spaced in period frequency peaks suggest that these are the modes with the same degree, ℓ , azimuthal order, m , and consecutive radial orders, n . According to Pápics et al [1], the frequencies are associated with prograde dipole modes ($\ell = 1, m = +1$).

In order to check whether this statement is valid if the effects of rotation are included, both in the equilibrium and pulsational calculations, we constructed a grid of rotating stellar models within the 3σ error box in T_{eff} and $\log g$. To this end we used the MESA code [10–12] considering a wide range of the rotational velocity, from $V_{\text{rot}} = 62$ km s⁻¹ to the upper limit of the validity of the traditional approximation. As the upper limit we adopted 200 km s⁻¹ which is about a half of the break-up velocity. The step was $\Delta V_{\text{rot}} = 1$ km s⁻¹. We included various rotational mixing mechanisms, i.e., dynamical shear instability, Solberg-Høiland instability, secular shear instability, Eddington-Sweet circulation and the Goldreich-Schubert-Fricke instability [see 11, 13, 14]. We assumed the initial hydrogen abundance, $X_0 = 0.7$, metallicity $Z = 0.017$, the chemical mixture of Asplund et al. [15], and the overshooting parameter in exponential description, $f = 0.02$. Three commonly used opacity data were adopted: OP [16], OPAL [17] and OPLIB [18, 19].

Then, we calculated nonadiabatic pulsation models in the framework of traditional approximation (here the step in V_{rot} was decreased to 0.1 km s⁻¹) for modes which seemed to be good candidates to reproduce observed series of frequencies, i.e., (1, +0), (1, +1), (2, +0) and (2, +1).

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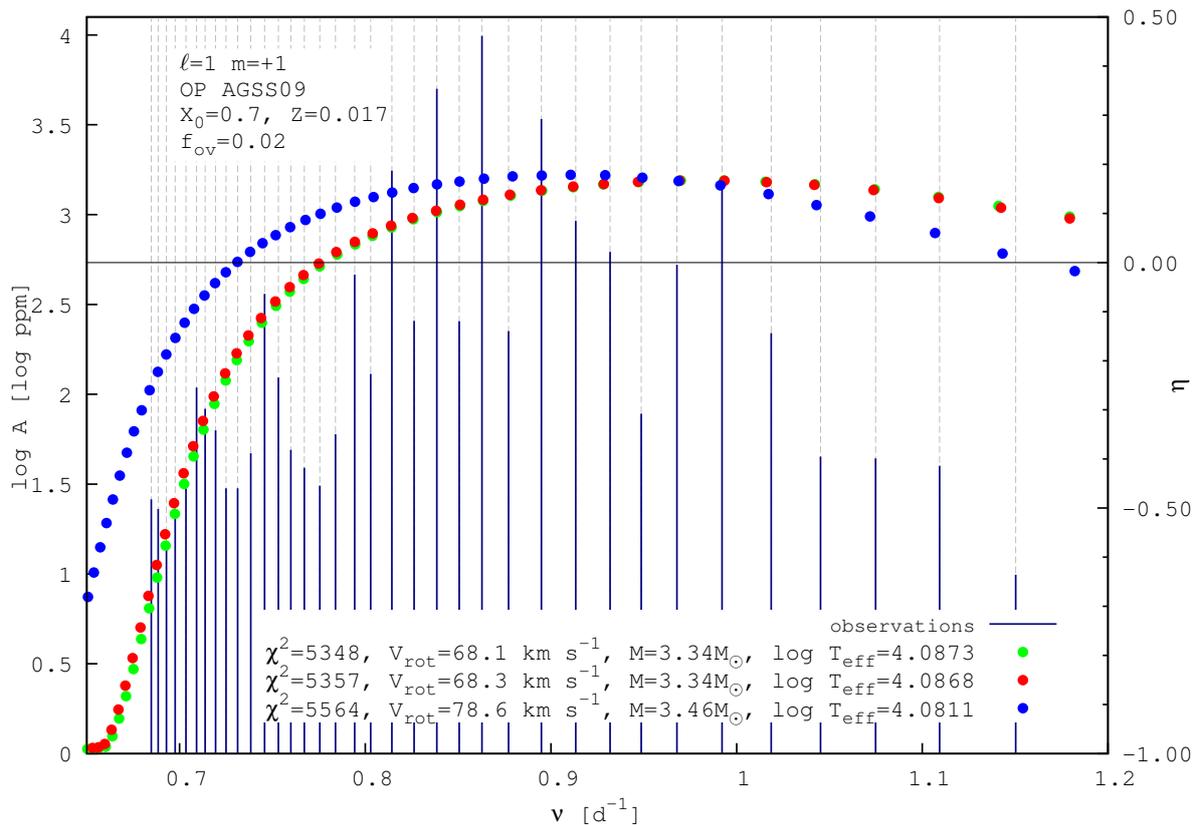


Figure 1: The best seismic models calculated with OP opacities. The observed frequencies and their amplitudes are plotted with vertical lines (left Y-axis). Colour circles mark theoretical frequencies and their instability parameter, η , can be read on the right Y-axis.

Since for modes other than (1, +1) the best models give worse quality of the fit, χ^2 (defined as in Moravveji et al. [2]), by the order of magnitude, we confirm that the frequencies in the series can be associated with the prograde dipole modes.

In Fig. 1, the theoretical frequencies of (1, +1) modes for the best three OP models are compared with the observed ones. The parameters of these models are summarised in Table 1. Without a doubt, the quality of fitting needs improvement. For the best models, we obtained the values of χ^2 of the order of 5500 which is a value almost three times higher than the one obtained by Moravveji et al. [2]. This is because in our calculations we fixed the metallicity and the overshooting parameter compared to the cited authors. Moreover, Moravveji et al. fitted the coefficient of the extra diffusive mixing in the radiatively stable envelope whereas we employed rotational induced mixing with fixed coefficients. In Fig. 1 on the right Y-axis it is also shown the instability parameter η ($\eta \leq 0$ – stable mode, $\eta > 0$ – unstable mode). As one can see, modes with the lowest frequencies in our best models are predicted to be stable. This is obviously contrary to the observations and needs to be improved.

The quality of the fit is quantitatively the same for each considered opacity source but for models with OPLIB opacities the theoretical instability domain is in an excellent agreement with the observed frequencies. This is

shown in Fig. 2, in which three best OPLIB models are plotted. As one can see only 3–4 modes are marginally stable, $\eta \approx 0$. Parameters of these models as well as of those obtained with the OPAL opacities are summarised in Table 1.

Then, we recalculated the best OPLIB model with different values of the metallicity and overshooting parameter as well as with the modified OPLIB opacity profile. The modifications of the OPLIB data consisted of an enhancement of the opacity at the depths corresponding to temperatures $\log T = 5.3$, 5.46 and $\log T = 5.06$. The increase of the opacity at $\log T = 5.06$ mimics the new opacity bump identified in Kurucz models by Cugier [20]. The modified models are shown in Fig. 3. The increase of the opacity at $\log T = 5.3$ by about 50% gives theoretical instability in the whole range of the observed frequencies. Moreover, for each observed frequency we found a corresponding unstable mode. Increasing opacity at $\log T = 5.46$ helps in exciting low frequency modes whereas the instability of high frequencies is unchanged. On the other hand, adding the Kurucz bump results in reducing the pulsational instability, both, at low and high frequencies. Larger value of the metallicity shifts the instability domain towards higher frequencies whereas more effective overshooting from the convective core acts in the opposite direction.

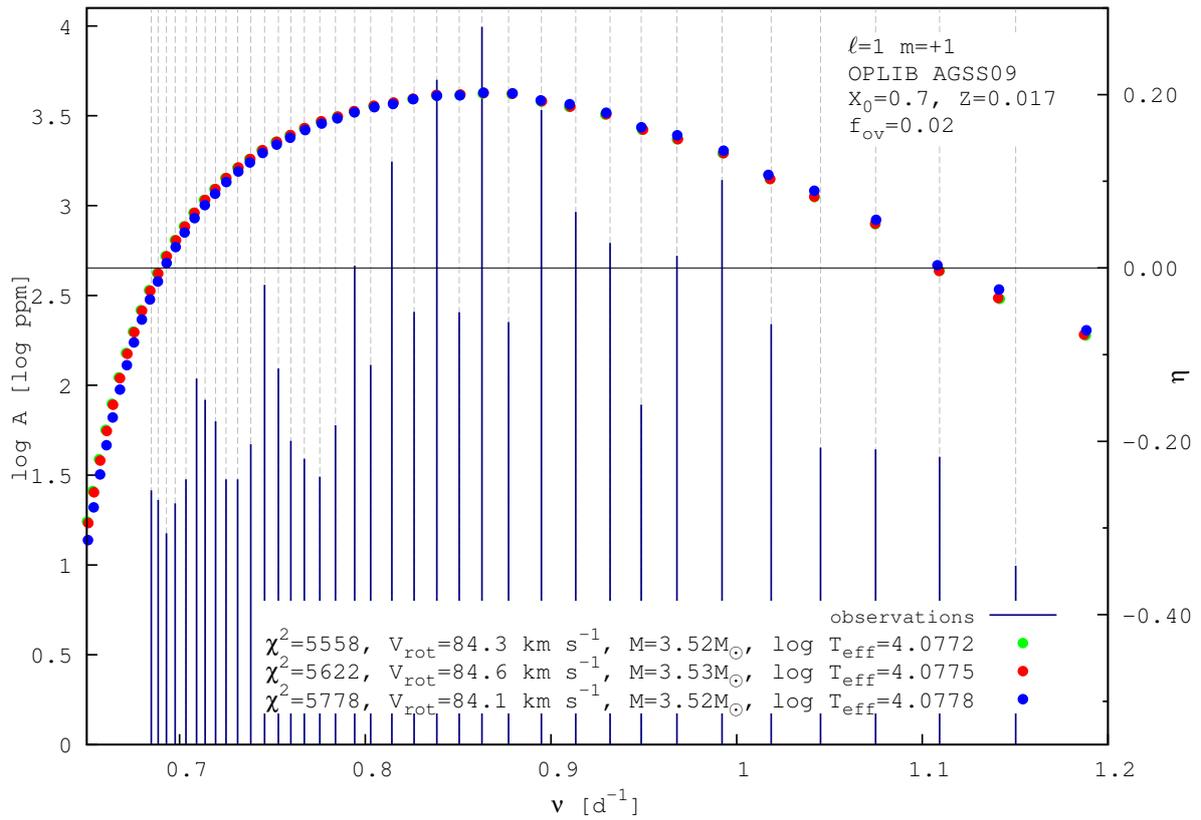


Figure 2: The same as in Fig. 1 but OPLIB models are shown.

Table 1: The parameters of the best seismic models. Column 1 – opacity data (#1 – OP, #2 – OPAL, #3 – OPLIB); Column 2 – mass (in the solar mass units) Column 3 – logarithm of the effective temperature; Column 4 – logarithm of the luminosity (in the solar luminosity units); Column 5 – central hydrogen abundance; Column 6 – rotational velocity (in km s^{-1}); Column 7 – measure of the fitting quality.

op	M	$\log T_{\text{eff}}$	$\log \frac{L}{L_{\odot}}$	X_c	V_{rot}	χ^2
#1	3.340	4.0873	2.222	0.42	68.1	5348
#1	3.340	4.0868	2.224	0.42	68.3	5357
#1	3.460	4.0811	2.327	0.35	78.6	5564
#2	3.510	4.0807	2.375	0.31	83.3	5786
#2	3.460	4.0834	2.336	0.34	78.8	5851
#2	3.510	4.0801	2.376	0.31	83.5	5998
#3	3.520	4.0772	2.371	0.30	84.3	5558
#3	3.525	4.0775	2.373	0.30	84.6	5622
#3	3.520	4.0778	2.370	0.31	84.1	5778

3 Conclusions

Our calculations confirmed Pápics et al. [1] finding that the 36 quasi-equidistant in period frequencies observed in KIC 7760680 are most probably associated with the consecutive prograde dipole modes. However, our best models have slightly higher masses (from $3.340 M_{\odot}$ to $3.525 M_{\odot}$ depending on the opacity data) compared to $3.25 M_{\odot}$ obtained by Moravveji et al. [2]. The reason is that we

used rotating evolutionary models which give lower effective temperature for the same mass. Rotational induced mixing can contribute to the differences as well. We got a little worse quality of the fit, $\chi^2 \sim 5500$, compared to the cited authors, $\chi^2 \sim 2000$ but in our calculations we have fixed the metallicity and the parameter of the core overshooting, which Moravveji et al. [2] set as free. It is prominent that the instability domain of the $(1, +1)$ modes obtained with the OPLIB data (see Fig. 2) nearly covers the range of the observed 36 frequency peaks. A slight increase of the opacity at $\log T = 5.3$ gives an excellent agreement. On the other hand, adding the Kurucz bump at $\log T = 5.06$ spoils the agreement. Finally, it should be added that series of frequencies equidistant in period may be accidental as they can be reproduced by modes of various angular numbers (ℓ, m) ; see e.g. [21]). Therefore, it is desirable to confirm the results of mode identification using another method, e.g., using multicolour time-series photometry.

Acknowledgements

This work was financially supported by the Polish National Science Centre grant 2015/17/B/ST9/02082. Calculations have been carried out using resources provided by Wrocław Centre for Networking and Supercomputing (<http://wcss.pl>), grant no. 265.

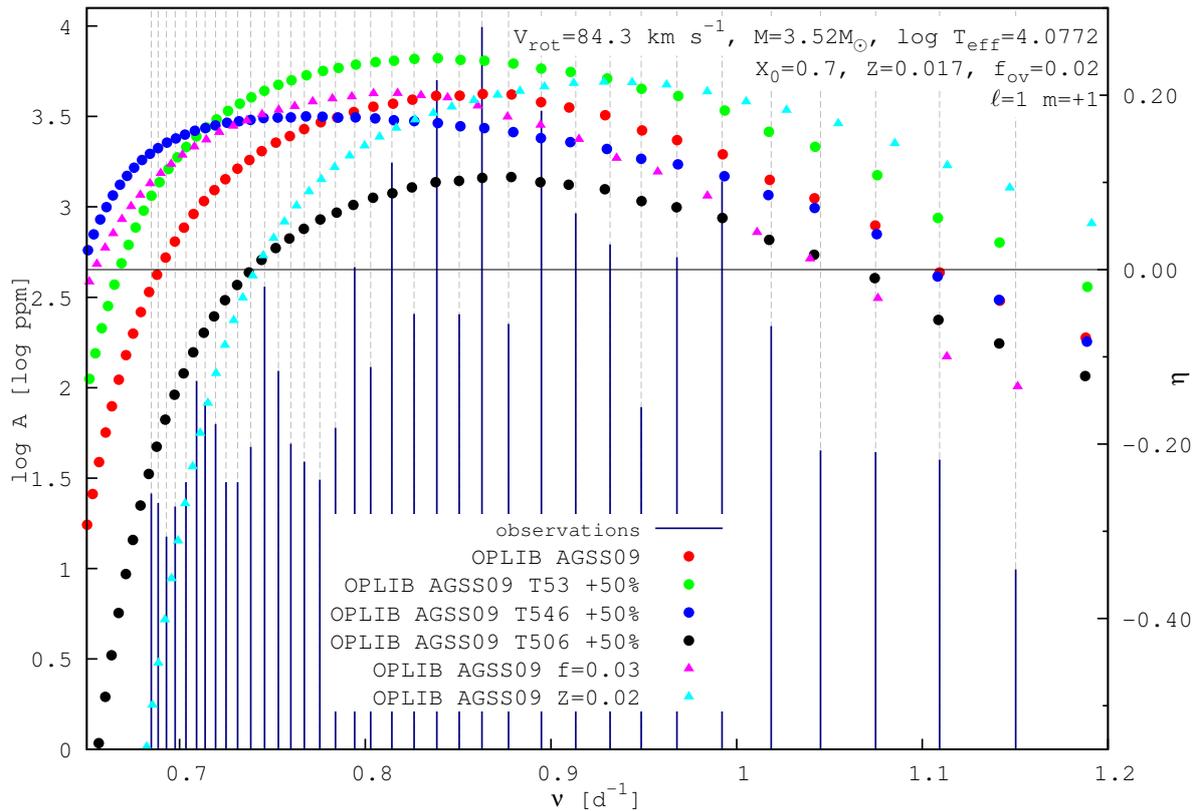


Figure 3: Best OPLIB model recalculated with increased OPLIB opacities by 50% at $\log T = 5.30$ (green circles), at $\log T = 5.46$ (blue circles) and at $\log T = 5.06$ (black circles) as well increased overshooting parameter (magenta triangles) and increased metallicity (cyan triangles). Original OPLIB model is marked by red circles. The coordinates meaning is the same as in Fig 1.

References

- [1] P.I. Pápics, A. Tkachenko, C. Aerts, T. Van Reeth, K. De Smedt, M. Hillen, R. Østensen, E. Moravveji, *Astrophys. J.* **803**, L25 (2015)
- [2] E. Moravveji, R.H.D. Townsend, C. Aerts, S. Mathis, *Astrophys. J.* **823**, 130 (2016)
- [3] U. Lee, H. Saio, *Astrophys. J.* **491**, 839 (1997)
- [4] R.H.D. Townsend, *MNRAS* **340**, 1020 (2003)
- [5] R.H.D. Townsend, *MNRAS* **343**, 125 (2003)
- [6] R.H.D. Townsend, *MNRAS* **360**, 465 (2005)
- [7] R.H.D. Townsend, *MNRAS* **364**, 573 (2005)
- [8] W.A. Dziembowski, J. Daszyńska-Daszkiewicz, A.A. Pamyatnykh, *MNRAS* **374**, 248 (2007)
- [9] J. Daszyńska-Daszkiewicz, W.A. Dziembowski, A.A. Pamyatnykh, *Acta Astron.* **57**, 11 (2007)
- [10] B. Paxton, L. Bildsten, A. Dotter, F. Herwig, P. Lesaffre, F. Timmes, *Astrophys. J. Suppl.* **192**, 3 (2011)
- [11] B. Paxton, M. Cantiello, P. Arras, L. Bildsten, E.F. Brown, A. Dotter, C. Mankovich, M.H. Montgomery, D. Stello, F.X. Timmes et al., *Astrophys. J. Suppl.* **208**, 4 (2013)
- [12] B. Paxton, P. Marchant, J. Schwab, E.B. Bauer, L. Bildsten, M. Cantiello, L. Dessart, R. Farmer, H. Hu, N. Langer et al., *Astrophys. J. Suppl.* **220**, 15 (2015)
- [13] A. Heger, N. Langer, S.E. Woosley, *Astrophys. J.* **528**, 368 (2000)
- [14] A. Heger, S.E. Woosley, H.C. Spruit, *Astrophys. J.* **626**, 350 (2005)
- [15] M. Asplund, N. Grevesse, A.J. Sauval, P. Scott, *Ann. Rev. Astron. Astrophys.* **47**, 481 (2009)
- [16] M.J. Seaton, *MNRAS* **362**, L1 (2005)
- [17] C.A. Iglesias, F.J. Rogers, *Astrophys. J.* **464**, 943 (1996)
- [18] J. Colgan, D.P. Kilcrease, N.H. Magee, J. Abdallah, M.E. Sherrill, C.J. Fontes, P. Hakel, H.L. Zhang, *High Energy Density Physics* **14**, 33 (2015)
- [19] J. Colgan, D.P. Kilcrease, N.H. Magee, M.E. Sherrill, J. Abdallah, Jr., P. Hakel, C.J. Fontes, J.A. Guzik, K.A. Mussack, *Astrophys. J.* **817**, 116 (2016)
- [20] H. Cugier, *Astron. & Astrophys.* **565**, A76 (2014)
- [21] W. Szewczuk, J. Daszyńska-Daszkiewicz, W. Dziembowski, *Interpretation of the oscillation spectrum of HD 50230 - a failure of richness*, in *Precision Asteroseismology*, edited by J.A. Guzik, W.J. Chaplin, G. Handler, A. Pigulski (2014), Vol. 301 of *IAU Symposium*, pp. 109–112