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Wrocław, 24 VI 2024

Referee report on the PhD thesis by Sachu Sanjayan entitled
Kepler photometry of two open clusters NGC6791 and NGC6819

The main subject of the dissertation is astroseismic study of pulsating subdwarf B (sdB) stars in NGC6791 using observational data from Kepler K2 mission and theoretical prescriptions from MESA and GYRE models. This is supplemented with the photometric study of the two open clusters (using the data from the same source) which includes variability survey, cluster's membership analysis and cluster-parameter's determination from the colour – magnitude diagrams (CMD). Both studied clusters belong to the population of old Galactic open clusters. In particular NGC6791 with an age of about 9 Gyr and an unusually high metallicity [Fe/H] = 0.3 seems to deny global chemical evolution of the Galaxy. sdB stars are very interesting objects of which some exhibit very complex and rich pulsation patterns resulting from both $p-$ and $g-$modes. The author provides interpretations for these patterns in terms of mode identification and determines basic parameters of studied stars.

The core of the thesis consists of a compilation of four papers (**P1** through **P4**) published in renowned astrophysical journals (MNRAS and AcA). Moreover there is an introductory chapter, which mostly presents in compact form the contents of the papers just mentioned. Three publications are multi-authored with mgr S. Sanjayan being the primary author, and the remaining paper is written by two co-authors with the PhD student being secondary author. Without a doubt mgr S. Sanjayan's contribution to all these works is leading one. This is further testified by coauthors statements. In my opinion, the fact of publishing own work in peer-reviewed journals (which obviously involves evaluation by experts in appropriate fields of astrophysics) is a sufficient reason to be awarded with a PhD degree.

The text is in Egnlish, except one version of abstarct given in Polish. Abstract is followed by **Introduction** which is a main part written especially for this thesis. In this section author gives comprehensive description of the hot sdB stars, emphasizing the possible scenarios of their origin and the crucial role of the mass loss. I found very interesting a subsection about occurance of these stars in stellar clusters, where also globulars are mentioned. Next, Kepler CCD observations and a method of light curve derivation from them are presented. Moving to the topics of pulsations in hot sdB stars PhD student describes known subtypes of these variables and discusses possibilities of mode identification based on the Fourier spectrum only, that is searching for patterns in detected frequencies (rotational splitting for $p-$ and $g-$modes) or periods (asymptotic approximation for $g-$modes). This methodology was subsequently used for mode identification in pulsations of three sdB variables (sdBV) which comprises the contents of paper **P1**. The results from **P1** are next used in forward modeling of pulsations in four sdBVs (this includes two stars discussed in **P1**) using MESA evolutionary models and adiabatic pulsations from GYRE, originally presented in publication **P2**. In addition, the author presents results from papers **P3** and **P4** of the survey of NGC6791 and NGC6819, respectively, which include search for variables stars, cluster membership analysis and cluster's parameter determination from CMDs. The account about searches for variable stars in studied clusters lacks mention of the recent independent work of Colman et. al (2022), where the same Kepler data were processed (although this paper is referred to in **P3** and **P4**). The last subsection of **Introduction** lists the most important results together with inevitable problems/simplifications which should be addressed in a future.

The first paper in the compilation, **P1**, reports analysis of light curves of three pulsating sdB stars in NGC6791, B3, B4 and B5. The authors used archival spectra of studied stars to redetermine their atmospheric parameters and to search for radial velocity variability. In the sample of 35 cluster stars they found radial-velocity excess in three sdB stars (B3, B5, and B6) which might indicate they are binary systems. The light curves were derived from Kepler super-stamp CCD frames taken in long cadence regime. The authors focused on searching for all variables in the observed central field of the cluster and the results of this search are presented in papers **P3** and **P4** where the same procedure was applied to the Kepler data for another open cluster, NGC6819. The approach is very interesting and starts with photometry for every pixel and next looking for variable signal using Fourier transform. It resembles the pixel method used in processing ground-based CCD frames of globular clusters with the image subtraction method. Then for every variable object a custom aperture is defined and flux photometry is determined. Kepler CCD frames show huge spatial undersampling and it is not clear what is shown as a background in Fig. 6. Cluster membership is checked using proper motions and paralaxes from Gaia EDR3. It is found that all sdBVs belong to the cluster with 100 % probability. I cannot, however, understand (and this is in fact crucial for membership of all stars in both clusters studied in **P3** and **P4**) why "stars with P(5D) $>$ 0.5 are classified as almost certain members"? In my opinion this limit is too low. The main part of **P1** is computation of amplitude spectra for sdBVs in NGC6791 and detection of (quasi)equidistant sequences in frequency and period. The authors use detected multiplets (in frequency) and period spacings to assign radial (n), modal (l) and azimuthal (m) orders of observed periodicities. It should be noted, that in this way modal identification was performed for most of the detected frequencies, only those of very low amplitude were unclassified. Estimated rotational periods show relatively large spread which naturally can be explained by differential rotation inside analyzed variables. This is quite common phenomenon in pulsating stars.

The most important achievement of the thesis is presented in paper **P2**. Mode identification done in paper **P1** was used here to perform astroseismic modeling of two pulsating sdB stars from NGC6791, B3 and B4. The same procedure was applied to two field sdBVs for which modal information was taken from Baran and Winans (2012). MESA package was used to generate a grid of evolutionary models of extreme horizontal branch stars (with central Helium abundance Y down to 0.1) and adiabatic pulsation periods were calculated with the GYRE code. The results are very encouraging although not for every star obtained fits were unique depending on the assumed constraints. Since rotation was not considered in theoretical period calculations, only central components of multiplets were used.

The authors adopted two approaches in matching observed with calculated periods, one without any constraints on physical parameters and the other with assumed spectroscopic estimates of $T_{\rm eff}$ and $\log(g)$. Moreover, but only for cluster's members, additional approach with constrained age and metallicity was used. As stated by authors, unique or narrow range of best models were found for analyzed variables with the use of spectroscopically constrained approach. Interestingly, it turned out that for two cluster stars significantly different solutions were obtained from fits with assumed cluster age and metallicity. The authors point out, however, that these stars might be components of the binary systems and the age of NGC6791 is likely not a reliable contraint. Contrary to the case of B3 and B4, for which the grid of models covers very well derived best fits (as can be seen in Fig. 2), the best models of analyzed field sdBVs only mariginally overlap with the space of all evolutionary models (Fig. 3) with KIC11179657 being an extreme case indicating it is in the final stages of HB evolution. It is possible, that assumption of the single-star evolution is not correct for this variable. It should be emphasized, that the work presented in paper **P2** is a significant step toward advancing the application of the astroseismic analysis to probing of sdB star's interiors. The authors propose further improvements to this method on the theoretical side, in particular consideration of the non-adiabatic pulsation models.

Detailed analysis of stars in the Kepler fields of NGC6791 and NGC6819 is presented in publications **P3** and **P4**, respectively. These two papers report actually analysis ot the same kind and thus I shall review them together. They obviously result from publication **P1** and the primary scientific purposes of the thesis, that is a search for and analysis of pulsating sdB stars. Quite possibly at least some work presented in **P3** and **P4** was done before publication of **P1**. Anyway, **P1** is a first paper in the series and thus contains all details of the photometric reductions of the Kepler CCD frames and derivation of the light curves of variable stars. It should be noted, that the same sample of Kepler data were independently analyzed by Colman et al. (2022). They used, however, different method for photometry based on simplified image subtraction. The work of mgr S. Sanjayan and coauthors is definitely superior in comparison to Colman et al. (2022) in respect of variability survey, because they searched every pixel whereas Colman et al. (2022) derived light curves only for stars listed in the KIC. It is not clear if the PhD student cross-matched his findings with those already identified as variables by Colman et al. (2022) and the numbers of new variables given in **P3** and **P4** are correct. The authors describe in more details (in compariosn to **P1**) the procedure of cluster's membership determination based on the fitting of the multi-Gaussian model to the astrometric data from Gaia EDR3 catalogue. I do not understand, why "if the uncertainities were larger than 50 %, we considered corresponding parameters to be error-free".

Based on flux changes, detected variables were assigned to the three classes: pulsators, rotating and eclipsing stars (not counting unclassified variables). I think, the tables listing properties of these stars should include also probability of cluster membership. This information would be very usefull due to the very low limit adopted for cluster membership (only 50 %). Pulsating blue stragglers found in NGC6819 were studied in detail by Guzik et al. (2023) with mgr S. Sanjayan being a coauthor. Moreover, analysis of numerous solar-like pulsators from both clusters is underway. Next, almost sure cluster members (probability > 90 %) were used to construct CMDs in the Gaia photometric system, G vs. $(B_{\mathrm{p}} - R_{\mathrm{p}})$. The fit of MESA isochrones to these CMDs was performed and cluster's distances and ages were determined, which agree very well with previous estimates. The authors do not provide any information on the goodness of the isochrone fits. It is not stated how fitting was done, perhaps some kind of least-squares method was used. All four main parameters, $(m - M)_G$, $E(B_{\mathrm{p}} - R_{\mathrm{p}})$, age and [Fe/H], were adjusted in the fitting and as expected it was not possible to find a unique solution. The obvious cause of this, as authors notice in **P4**, is a degeneration of solutions in which different values of fitted parameters give fits of the same quality. Thus one may expect rather "broad" relations between goodness of the fit and derived/assumed input parameters. In this context it is strange that authors provide estimates of these parameters with rather high accuracy of 0.01 mag for magnitude-related parameters and uncertainty of metallicity of only 0.02. How these errors were determined? Looking at Fig. 5 of **P3** and Fig. 7 of **P4** it seems that the MS phase is not very well fitted by isochrones. Instead to the fiducial sequence the fit was made to the blue edge of the MS and TO region in the CMDs. How was it forced? It is also not clear which two isochrones are shown in figures just mentioned. The most valueable outcome of publications **P3** and **P4** is a complete identification of variable stars of various types in the very central regions of two old open clusters supplemented with an information on their cluster's membership.

The layout of the work is correct. The text is written in a fluent and readable manner. The only language error I found is "Fluxes ... was divided" (p. 11 of Introduction). The author does not avoided minor typographical errors related to the specific LaTeX typesetting system used. These include, for example, the use of a roman font for symbols denoting physical parameters (e.g. $\mathrm{T_{eff}}$ instead of $T_{\rm eff}$, log g instead of $\log g$, G instead of G, $\mathrm{B_p}$ instead of $B_{\rm p}$, O-C instead of $O-C$) and invalid use of mathematical style of TeX (e.g. [Fe/H]=-0.1−+0.1 instead of [Fe/H] $= -0.1\pm0.1$).

The work also contains the following minor errors mostly due to the unacceptable simplifications. I think the term "overtone" should be used only for radial modes. Nonradial modes are identified with radial order, but this does not mean they are overtones. Even if there are different points of view on this subject, the use of this word in the phrase in p. 15 of Introduction, "period spacing between two consecutive radial overtones" or "consecutive radial overtones" in **P2** is completely incorrect and misleading. I would rather write "spacing between two nonradial modes with consecutive radial orders". Units are missing in "... parallaxes between zero and one." (**P1**). The author uses word "prewhitening" incorrectly. Whitening means removing from data any periodic signal. Thus, prewhitened might be light curves, not frequencies, as in "to prewhite frequencies", "We pre-whitened a few tens of frequencies", "most of the frequencies are pre-whitened" (Sec. 3.2 of **P1**), "Pre-whitening of non-coherent frequencies" (Sec. 3.3.3 of **P1**). Photometric reddening affects only color indices, not apparent magnitudes. Therefore, in my opinion, the term "de-reddened distance modulus" is incorrect. It would be more appropriate to use e.g. "extinction-corrected" instead of "de-reddend".

The PhD thesis of mgr S. Sanjayan contains original and valuable results based largely on public observational material of different type. The author has proven himself to have high skills in processing photometric, spectroscopic and astrometric data and computation of theoretical evolutionary and pulsational models of sdBVs. The outcome of this dissertation constitute an important contribution to research in the field of asteroseismology and its application to the interesting class of pulsating stars. Furthermore, the form of the thesis indicates high activity of the author in publication of scientific articles and very good orientation on the topics of the work.

To sum up, I state that the presented dissertation meets the formal and customary requirements for doctoral theses. I am requesting that mgr S. Sanjayan be admitted to further stages of the doctoral process.