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Report of the doctoral dissertation by Sumanta Kumar Sahoo, entitled „TESS photometry of hot subdwarf" supervised by dr hab. Andrzej Baran, prof. UP

The PhD thesis of Sumanta Kumar Sahoo has a form of a collection of five articles published in the refereed journals: four in MNRAS (**Paper I, II, III and IV**) and one in PASA (**Paper V**). These are thematically related papers and the title of the thesis corresponds to their content. The articles concern the analysis of photometric and spectroscopic observations of pulsating hot subdwarfs. In particular, they focus on the search for new pulsating sdB stars using the time-series space photometry from the *TESS* mission. Additionally, for a sample of stars, ground-based spectroscopy is used to determine the basic stellar parameters, like effective temperature, surface gravity, helium content and to make a spectral classification. An attempt was also made to interpret the oscillation spectrum of selected sdB pulsators. All five articles are multi-authored, but the contribution statements of the co-authors point to the dominant role of the PhD student. However, the leading author of **Paper II** is the supervisor. The collection of articles is preceded by an **Abstract** in English and Polish as well as a 20-page **Introduction**.

The **abstract** provides concise information about the content of the thesis and in general in has a correct form. However, I have the three remarks:

1) What does the PhD student understand by "sophisticated mode identification techniques used in his thesis? In the thesis, he just makes use of the well-known asymptotic relation for the high-order g modes.
2) Then, one can read: "We fit our observationally derived results with the MESA pulsation grid to derive the physical parameters of these stars." In the Polish version it sounds "Dopasowujemy nasze obserwacyjne wyniki do siatki modeli pulsacyjnych (MESA), aby wyznaczyć parametry fizyczne tych gwiazd." I believe that we always fit theory to observations, not vice versa.
3) The Polish version could be written better. It sounds like a calque from English using Google translator.

The **Introduction** contains a short description of the properties of hot subdwarfs and their pulsations as well as the general summary of main results obtained in the five articles, which constitute the basis for applying for a doctoral degree. I found a few important omissions and inaccuracies in theoretical part.

1) When writing about the excitation mechanism of pulsation in sdB stars one cannot fail to mention the role of radiative levitation of iron. Pulsational instability in these stars is caused by local accumulation of Fe in the driving zone, what is a consequence of the diffusive equilibrium between gravitational settling and radiative levitation.

2) Describing the pulsational mode, the PhD student writes on page 5 "The geometry of a pulsation mode is defined by three spherical harmonic parameters (n, l, m)." Only the numbers (l, m) are indexes of the spherical harmonics and describes the mode geometry. The radial order n describes rather the shape of eigenfunctions.
3) Here and in the further part of the PhD thesis. Rather the term "mode degree" is used not "modal degree".
4) As for the disc averaging effect, it is true that the mode visibility decreases with increasing l, but one has to remember about two facts. First, in the case of high precision space photometry, the modes with l >2 cannot be excluded and actually are needed to account for all observed peaks. Second, the geometrical term (2+ l)(1- l) in the linear expression for the photometric amplitude increases as l increases. Thus, the photometric amplitude does not need to drop with l as quickly as the co-called disc averaging factor b_l.
5) Section 1.4 on the mode identification.
    - The fact that the Ledoux C_{nl} constant tends to zero for high-order or high-degree p modes and to (l^2+ l) for high-order g modes is a well-known property (e.g. Ledoux 1951, Unno et al. 1989) and it was not derived by Charpinet et al. (2002).
    - In Eqs. (1.3), (1.4), P_0 is not the period of the radial fundamental mode. It would not have a physical meaning. P_0 stands for the buoyancy travel time, and it is expressed by an integral from the Brunt-Väisälä frequency over g-mode propagation cavity. The radial fundamental mode is of the order of the dynamical time scale. This misinterpretation of P_0 occurs also in Paper IV.
    - Page 15, the ratio of the period spacing of l=1 to l=2 modes is √3 not 1/√3. And l=2 to l =3 is √2.

In **Paper I**, by S. K. Sahoo, A. S. Baran, S. Sanjayan and J. Ostrowski, the authors aimed to find sdB pulsators using time-series space photometry from the first year of the *TESS* mission. To this end they used full-frame images (FFI) taken every 30 min (long cadence, LC) and containing the entire field of view. Due to LC mode, the search was limited to the variability up to 277 μHz, i.e., to *g*-mode pulsations in sdB stars. The observations covered the southern ecliptic hemisphere. A huge technical work was done during the target selection and flux extraction. To this end, the database by Geier (2020) was used which contains confirmed sdB stars and the candidates. Besides, targets with non-sdB spectral classification were included. In total, more than 20 000 stars were analysed and for each of them the amplitude spectra were calculated.
To extract the light curves from *TESS* FFI, the authors used standard tools as Lighkurve and Eleanore. In total, 1807 variables were found among which were 2 new sdB pulsators and 83 pulsators without spectral classification. The remaining variables were, among others, binaries including two known HW Vir systems and two nova stars. Most of the results from **Paper I** are available on-line in tabular form. Because the light curves were not corrected for the contamination effects, most objects had to be treated as candidates.
In the next step, the authors selected five out of 83 pulsators which have a significant number of high-amplitude peaks and were suspected to be the sdB stars. The aim was to find the quasi-equal period spacing assuming that the signals correspond to l=1 or l =2 modes. In the case of the star TIC 906337576, some indications for rotational mode splitting were found. According to the co-author statements, the contribution of the PhD student to **Paper I** is 80%.

Paper II contains the results of the search for pulsating sdB stars from *TESS* FFI data collected for the northern ecliptic hemisphere. Again, many stars were treated as candidates because of neglecting the contamination effect. The same procedures and the same tools to extract the light curves were used as in **Paper I**. The search resulted in the identification of 506 variable star candidates, including 13 new pulsating sdB stars. Most of these objects do not have the spectral classification. The authors selected the three sdBV candidates whose amplitude spectra resembled those of this type of pulsators. As in **Paper I,** the period spacing was searched typical primarily for dipole modes. Besides, a lot of binary candidates were detected including 33 eclipsing systems. For 12 EB candidates, the authors derived the period and tried to study its changes using the O-C method, but no firm conclusion has been received. As in the case of **Paper I**, most of the results are available on-line in tabular form. The paper was led by the supervisor dr hab. Andrzej Baran but according to his statement and that of the other two co-authors, the doctoral student's contribution is 65%.

Paper III is a verification of the results obtained in **Paper I** and **Paper II**. The article contains an in-dept contamination analysis to identify the true source of variability. To this end, the light curves was extracted for each pixel and amplitude spectra were computed. Then, the Pan-STARRS or DSS images were overlapped with *TESS* target pixel files. In addition, the authors analyzed the 10 min FFI from the 3rd and 4th year of the *TESS* mission. Considering the contamination effect revealed 1141 false positives out of 2313 presented in Paper **I** and **II**. Many variables (451) could not be verified because of too low signal in individual pixels. Ultimately, 721 objects from Paper I and II passed the contamination test and were confirmed as variables. Moreover, 682 more variables were found during this analysis. That gave 1403 variables stars in total. In the next step, the 10 min FFI data were analyzed for stars exhibiting rich signal around 277.7 μHz. The argument for this approach was that this was the value of the Nyquist frequency in Paper I and II. Out of 78 selected targets, 24 showed multiperiodicity with many frequencies larger than 277.7 μHz. Based on spectra from SAAO, the authors ended up with 11 new sdB pulsators. No details on spectroscopic analysis were provided and no spectra of these stars were shown. The product of the analysis in **Paper III** is very rich online material. The co-author statements give the 70% contribution of the doctoral student to this paper.

Paper IV is devoted to more advanced analysis of the three sdB pulsators. Adopting the values of effective temperature and surface gravity from the literature as well as the Gaia parallaxes, the angular diameter and interstellar extinction were derived from the fitting of the synthetic SED to the observed one. Having these parameters, the values of radii, masses and luminosities were estimated. In the next step, the TESS light curves for the three stars were analyzed. These observations are from single sectors in the SC (Short Cadence, 120 s) mode.
The Fourier analysis revealed 22 frequencies in SB 459, 37 in SB 815 and 22 in PG0342+026. Then, the quasi-equal period spacing was searched and the degrees l=1 or l=2 were assigned to almost all peaks. In the case of SB 815 and PG0342+026, some candidates for trapped modes were proposed using the echelle diagrams and the reduced period diagrams. In the last section of the paper, the position of the three stars on the log g vs logT_{eff} diagram was compared with single-star evolutionary tracks taken from the paper of Ostrowski et al. From this comparison preliminary estimates of the evolutionary stage, the helium content in the core and the mass of the hydrogen envelope is given. According to the doctoral student statement, his contribution to **Paper IV** is 60%, but there are no declarations from all co-authors.

In **Paper V,** the analysis of g-mode pulsations of six sdB stars is presented. For the four stars, the authors collected low-resolution spectra from LAMOST, SAAO, APO and IAO. Then, the values of effective temperature, surface gravity and the abundance of helium to hydrogen were determined. It was done by means of the program XTGRID which computes the theoretical spectra from TLUSTY NLTE model atmospheres. For the remaining two stars, parameters from the literature were gathered. Then, the frequency analysis of the TESS light curves was performed. All stars were observed in the SC mode and four in the USC mode (ultra-short cadence, 20 s). One star was observed in a single sector and five stars in 3, 6, 4 and even 7 sectors. To extract frequences Period04 software was used this time and the S/N=5.0 detection threshold applied. The identification of *l* started by assuming that all highest amplitude peaks are dipole axisymmetric modes if they fit into a sequence of period spacing of about 250 s. Then, the lower-amplitude peaks were included into this sequence if they could be expressed as a multiple of ~250 s. Then, the radial order *n* was assigned using, as in the previous paper, an arbitrarily fixed offset n_l. These modes were used to find simple seismic models based on evolutionary models from MESA and adiabatic computations of stellar pulsations from GYRE software. The evolutionary models were computed in the mass range 1.0-1.8 Msun, and the metallicity Z between 0.005-0.035. No information on opacities, initial hydrogen abundance, rotation, overshooting from convective zones, the mixing parameter α_{MLT} is given. All models which gave 1.5 times the minimum mean difference between the theoretical and observed periods were accepted. Table 5 lists the seismic models which meet this condition. There is a lack of information on metallicity and radial order.

In Sect.5 of **Paper V**, there is an interesting comparison and discussion on the content of n(He)/n(H) as a function of the effective temperature. The authors collected these determinations for more than 1500 sdB stars, of which 76 were pulsating. No pulsation amongst extremely rich He sdB stars was found, whereas the largest number of pulsators are those poor in helium. Finally, an attempt was made to allocate sdB pulsators to three Galactic populations (thin disc, thin disc, halo) depending on which pulsations dominate (p modes, g modes, p/g modes). However, a sample is too small to draw any firm conclusions. The study presented in Sect. 5 certainly deserves to be continued. According to the PhD student statement his contribution to **Paper IV** is 60%, but there are no declarations from all co-authors.

Remarks and comments:

1) In **Paper I** and **II**, for the sake of clarity, the method of calculating the amplitude spectra should be mentioned. The authors used the detection level of S/N=4.5. A short explanation should be given why 4.5. Moreover, the significance criterion is not consistent through the articles. Sometimes the value S/N=5 appears sometimes 4.5.
2) **Paper I** page 5516 and **Paper II** page 3842. It should say “The period spacing for high-order g modes” instead of “for higher degree modes”. Moreover, at least a short explanation should be given on how the relative radial order *n* was assigned to frequency peaks.
3) Judging from the frequency values, many of sdBV candidates could also be δ Sct or β Cep pulsators. As the case of TIC 362098036 has shown, a nearly equidistant period spacing can be accidental. TIC 362098036 appeared to be a main sequence B-type star. Another example is TIC 237597052, which was classified as B8 main sequence star in **Paper III**.

4) Treating dipole modes as most probable is a reasonable approach, but it should be remembered that this may not always be the case. Secondly, even a slow rotation can slightly change the mode frequencies. Thirdly, including low-amplitude modes in the asymptotic sequences is risky, because they can correspond to higher *l* modes of unknown azimuthal orders *m*. In the presented papers, some peaks assigned as *l*=1 or *l*=2 are at the edge of detection threshold or even below. It is highly probable that such peaks coincidentally reproduce the period spacing. Finaly, a part of the detected peaks may arise from algebraic combinations of frequencies of dominant modes. I found no discussion of these important issues in the thesis.
5) In Paper III, there is the information that Pan-STARRS and DSS for the contamination analysis were used. In the Introduction, the doctoral student mentions DSS, 2MASS and SDSS.
6) **Paper IV** is missing a lot of important information. They could be given in the Introduction.
   - which exactly model atmospheres were used to compute the Balmer and HeI lines and SED?
   - what were the values of projected rotational velocities and microturbulent velocity?
   - how was the helium abundance fixed in Tables 2, 3, 4?
   - why was the frequency resolution 1.5/T adopted and not the safer 2.5/T?
   - in which frequency range was the noise computed to determine the value of S/N?
   - how many harmonics and combination frequencies appeared during the analysis?
   - the first sentence of Section 4.2: "Multiplets are a result of stellar rotation that changes frequency of modes with the same modal degree and m≠0." Rotation (magnetic field or another symmetry breaker) does not change the frequencies of modes with m≠0. Rotation lifts the 2*l*+1 degeneracy and causes multiplets to appear.
   - what was the value of the initial hydrogen abundance, rotation, overshooting from convective regions, the efficiency of convection in the outer layers adopted for the used evolutionary tracks? What opacity data were adopted? All these parameters can significantly change the conclusions on a hydrogen envelope mass and helium content in the core. Besides, these evolutionary tracks neglect the effects of radiative levitation and gravitational settling, which are crucial, not only for the pulsation of these stars but for their physical properties in general. Finaly, one should be aware, that such simple single-star evolution cannot be relevant for sdB stars. Therefore, drawing such firm conclusions is not fully justified and at least a short text should be added to demonstrate that the doctoral student is aware of all these effects and resulting uncertainties.
   - on page 2855, it says: "SB 459 … still has more than half of its initial helium abundance available in the core." What initial abundance of helium? On page 2853, one can find Y=0.2703, but I presume it is not about this value.
7) remarks and questions to **Paper V**
   - why this time the S/N=5.0 threshold was used?
   - It would also be appropriate to provide a brief comment as to why the Period04 program was used this time.
   - dividing the observation into consecutive TESS sectors is a reasonable approach, but why the frequency analysis was not performed also for all the combined data?
   - I did not find in the paper by Dziembowski (1997) that the photometric amplitudes decrease as $1/\sqrt{l}$ if the degree *l* increases. There is only an asymptotic limit for the disc averaging factor, i.e., if $l \rightarrow \infty$ then certain integrals tend to $1/l^{3/2}$ but it depends on the limb-darkening law.
   - if only the frequencies of *l* =1 modes were fitted why modes up to *l* =4 were computed?
   - I do not understand the sentence "Since our calculated periods are based on adiabatic calculations we used preliminary mode identifications derived in this work." What mode

identification would be used for nonadiabatic calculations?

- the values of rotation, initial hydrogen abundance, convective overshooting and mixing length parameter should be given as all these parameters can significantly change the values of pulsational frequencies
- the information on metallicity and radial orders of seismic models in Table 9 should be provided. How do the theoretical values of *n* compare to the "observed" ones given in Tables 3-8?
- including radiative levitation is important not only for the mode excitation but it also change the mode frequencies. Also, nonadiabatic effects can affect high-order g mode frequencies.
- a comparison of the observed and theoretical oscillation spectrum would be of interest
- Given the above remarks, this simple seismic modelling I would rather treat as an exercise and first guess to more advanced and realistic seismic studies. Such seismic modelling should be performed simultaneously with the mode identification

8) in the introduction and the papers: “in function” → “as a function”

Summary

The doctoral student Sumanta Kumar Sahoo performed a lot of hard and time-consuming work when analyzing the TESS photometry. The light curves were extracted from the TESS Full Frame Images, which required the development of additional scripts to process individual pixels. The main goal of **Paper I, II** and **III** was to search for pulsating sdB stars and 11 such objects were found. However, as by-product S. K. Sahoo with the co-authors found 1403 variables of different type. This is an important result that makes a significant contribution to the search for variable stars in the TESS time-series photometry from FFI. This rich material can be useful for many researchers. One of the most important results of the doctoral thesis is the contamination analysis presented in **Paper III**. This is another important contribution showing how to tackle with crowed field in the TESS FFI data. All three papers delivered rich and useful on-line material.
The next important result is an assignment of the mode degree *l* to frequencies using the asymptotic-period spacing method. This is a good starting point for advanced seismic modelling of considered sdB pulsators, combined with a simultaneous identification of the numbers (*l*, *m*).
Finally, I found the discussion of the dependence of helium abundance on effective temperature for sdB stars, with special emphasis on pulsators, to be a very valuable result. This is the first inclusion of pulsating sdB stars into such comparison and these studies should definitely be continued.
It is worth to mention also that Sumanta K. Sahoo co-authored also the other eight papers mostly related to hot subdwarf stars.

I consider the doctoral thesis of Sumanta Kumar Sahoo to be a valuable contribution to the analysis of the TESS light curves and to the study of sdB pulsators. The thesis meets the criteria prescribed by the Polish law for a doctoral dissertation. Therefore, I request that this dissertation be admitted to a public defense.

Signed by /
Podpisano przez:

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