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Review report on the PhD dissertation „TESS photometry of hot subdwarf stars” submitted by Sumanta Kumar Sahoo

1. Basic information about the dissertation

Hot subdwarf stars are specific objects that still puzzle astronomers. They are located at the extremely hot part of the horizontal branch – the evolutionary stage with helium burning in stellar cores. They are devoid of outer hydrogen-rich layers, typical for other stars on the horizontal branch. Their masses are close to 0.5 $M_{\odot}$, and radii range from 0.15 to 0.35 $R_{\odot}$, resulting in high gravity acceleration $\log g$ between 4.0 and 6.5. They have thin, residual hydrogen atmospheres with masses of the order of 10^{-2} $M_{\odot}$ or less. The origins of such configurations are still a subject of debate. They invoke mechanisms of stripping off the outer, hydrogen-rich layers of evolving stars, for instance, due to mass transfer in binary systems. Hot subdwarf stars are divided into classes depending on their effective temperature, which ranges between 20,000 and 100,000 K, and spectroscopic properties. Some hot subdwarfs exhibit photometric variability resulting from multi-mode non-radial pulsations. They are driven by the κ mechanism induced by the iron opacity bump. Applying the asteroseismological methods allows stellar parameters to be determined accurately and compared with theoretical models. Uninterrupted photometric time series, acquired with space-borne instruments, provide unprecedented data flow, shedding new light on the nature of variable hot subdwarf stars.

The PhD dissertation by Sumanta Kumar Sahoo aims to (1) discover new hot subdwarfs and (2) analyse variability for 9 identified hot subdwarfs. It is based on photometric time series provided by the Transiting Exoplanet Survey Satellite (TESS). The first goal was achieved by verifying the variability of hot subdwarf candidates spread over the sky. The light curves were extracted from full-frame images (FFIs) and subjected to the Fourier analysis, leading to variability identification of 15 likely new pulsating hot subdwarfs. The second goal was achieved by analysis of photometric data from short-cadence subframes, allowing for brightness probing with the 2-minute resolution. Many pulsation frequencies were detected for each star, and mode identification was performed.

The doctoral dissertation of S. K. Sahoo is a thematically consistent collection of five articles published in the high-ranked journals *Monthly Notices of the Royal Astronomical Society* (MNRAS) and *Publications of the Astronomical Society of Australia* (PASA). Chapter 1 is an introduction to the subject of hot subdwarf stars. The remaining chapters, numbered from 2 to 6, contain the individual papers. There is also the author's declaration of contribution, information about the author's supplementary research contributions, acknowledgements, abstracts in English and Polish, and contents. The bibliography used is listed at the end of Chapter 1. The structure of the dissertation can be considered entirely correct. A very high editorial level distinguishes the dissertation. It is written in excellent English, and sporadic linguistic errors (mainly typos) do not affect this assessment.

2. Substantive assessment of the dissertation

Chapter 1 presents the current state of knowledge on hot subdwarf stars. Section 1.1 provides a historical outline of research on stars of that type and the broad context of their studies. As hot subdwarfs of spectral type B (sdB) are the most common, also in the investigated sample, their detailed characteristics are provided, including pulsation variability in the scope of observations acquired with space-borne facilities such as the Kepler telescope and TESS. Examples of light curves attributed to pulsations in pressure (p) modes with typical timescales of minutes and to pulsations in gravity (g) modes with typical timescales of hours are shown. In sections 1.2–1.5, the narrative acquaints readers with TESS observations and methodological aspects of identifying pulsation modes. Section 1.6 places the studies in a broader context of the Galactic populations. The results obtained in chapters 2–6 are briefly summarised in section 1.7. The content of this chapter is a thoughtful and comprehensive review, getting non-expert readers familiar with issues presented in the subsequent parts of the dissertation. Introductory sections in articles presented in chapters 2, 4, 5, and 6 also show that S. K. Sahoo has general theoretical knowledge in astronomy and has become an expert in hot subdwarf stars.

Chapter 2 contains paper I, *A search for variable subdwarf B stars in TESS full frame images – I. Variable objects in the southern ecliptic hemisphere* (2020, MNRAS 499, 5508–5526). A sample of 20,642 targets was extracted from a database of sdB and sdB candidates provided by Geier (2020, A&A 635, A193). The FFIs acquired during the first year of TESS operation were reduced with the *Eleanor* and *lightkurve* packages to produce light curves. The long cadence mode of 30 minutes limited the search to g-mode pulsations. Amplitude spectra were calculated with the Fourier method, and signals with a signal-to-noise ratio greater than 4.5 were treated as positive detections. Two sdB pulsators were found among over 1800 variables of other types, including 26 variables with known sdB spectra, 83 non-classified pulsating stars exhibiting signals typical of g-modes in sdB pulsators, 83 eclipsing binaries (with two known HW Vir systems and four new candidates), 1535 other pulsators and non-eclipsing binaries, 2 novae, and 77 variables with non-sdB spectral classification. For 5 non-classified pulsators, it was possible to identify pulsation modes using the multiplet and period spacing methods. The results supported the sdB nature of those stars, which still demand spectroscopic confirmation.

Chapter 3 presents paper II, *A search for variable subdwarf B stars in TESS Full Frame Images – II. Variable objects in the northern ecliptic hemisphere* (2021, MNRAS 503, 3828–3847), which continues the survey initiated in paper I. The FFIs secured in the second year, after flipping the telescope to the northern ecliptic hemisphere, were reduced to produce low-cadence light curves for 4804 targets, carefully selected from the database provided by Geier (2020). Over 500 of them were found to reveal photometric variability. Among those variables, 13 were identified as likely new pulsating sdB stars. However, their amplitude spectra were not rich in modes, preventing further detailed analysis. Another 40 sdB stars revealed other variability types, mainly due to binarity. One was classified as an HW Vir system, just like another 5 variables without spectroscopic classification. Mode identification was performed for 3 candidates for pulsating sdB stars that remain spectroscopically unclassified.

The angular resolution of TESS cameras is relatively low, with pixels having 21 arc seconds on a side. That renders a high probability of flux contamination, especially for faint targets in crowded fields. This problem was investigated in paper III, *A search for variable subdwarf B stars in TESS Full Frame Images III. An update on variable targets in both ecliptic hemispheres – contamination analysis and new sdB pulsators* (2023, MNRAS 519, 2486–2499), presented in chapter 4. Observations acquired with the 10-minute cadence during the third and fourth years of the TESS mission were used to verify the variability status of 2995 targets. The shorter cadence allowed the authors to probe higher frequencies and update amplitude spectra, bringing 24 new variables with multiple frequencies, typical for pulsators. A dedicated procedure was developed to determine which targets contribute to the flux variability in a photometric aperture. It was based on an analysis of single-pixel test light curves. Here is my remark: in the text in section 2 of the paper, a 3×3 pixel aperture is mentioned, but 4×4 pixel apertures are displayed in figures 1–6. The targets were assigned to 6 specific contamination classes, reflecting all possible scenarios. Over 700 variable stars from papers I and II were confirmed as actual variables, and another 1141 targets were identified as false positives (known variables contaminating the survey's targets). For the remaining stars, their variability status remained unconfirmed. In addition, new spectra for 24 targets were analysed, and 11 new sdB pulsators were announced.

The survey presented in chapters 2–4 aimed to identify pulsating sdB stars missing in the TESS sample. Those new variables could be proposed to be added to a list of targets of interest and observed in the short or ultra-short cadence mode to probe higher frequencies, typical of the p modes. In total, 15 such stars were found. Another 33 subdwarfs showed flux variations of other types. For 66 sdB stars, no brightness variations were revealed. Among spectroscopically unclassified candidates for sdB stars, 133 objects were identified as likely pulsating sub-dwarfs due to specific features in their amplitude spectra. Building a more complete picture of the sdB population is undoubtedly an original and essential contribution. It may also trigger further studies of the sample, including analysis of high-cadence photometric time series and spectroscopic classification. My only critical remark to this part concerns the de-trending procedure applied to instrumental low-cadence TESS light curves. What algorithm was used, and with what parameters?

Chapter 5 contains paper IV *Mode identification in three pulsating hot subdwarfs observed with TESS satellite* (2020, MNRAS 495, 2844–2857). The periodogram analysis was performed for 3 pulsating hot subdwarfs based on short-cadence single-sector photometry from TESS. Although no multiplets were found, mode geometry was partially constrained with the period spacing method based on the echelle diagrams. Candidates for trapped modes were identified. Atmospheric parameters (effective temperature and gravity) were determined for one target (SB 459) from spectral analysis of a single spectrum acquired with the NTT/EFOSC2 in 2019. Fundamental stellar parameters (mass, radius, luminosity) were determined from spectral energy distributions. In addition, the evolutionary status of the three stars was discussed and illustrated in a gravity vs. effective temperature diagram. All three stars were found to be at the helium-burning stage in their cores, with SB 815 being much more evolved than the remaining two stars.

Paper V, entitled *Mode identification and period fitting in six pulsating hot subdwarfs* (2024, PASA 41, 41) and presented in chapter 6, continues the project initiated in paper IV. The Fourier analysis detected many frequencies in multi-sector short-cadence TESS photometry for five pulsating subdwarfs. For one target, single-sector observations were available. Only two targets were known as variable stars before the TESS era. New spectra were acquired for 4 objects using 2–3.5 m telescopes at the South African Astronomical Observatory, Apache Point Observatory, and Indian Astronomical Observatory, and the fundamental stellar parameters were determined. Again, the echelle diagrams were constructed for dipole and quadrupole modes. Evolutionary models were calculated using the commonly used MESA code, and pulsations models were generated using the GYRE code. The observations were compared with the grid of those models to determine the masses and radii of studied stars and the masses of their progenitors. The internal structure and evolutionary status were discussed. The 6 stars were found to occupy a helium-poor region in the updated helium content vs effective temperature diagram, where known hot subdwarfs were also plotted. Interestingly, no pulsators were found among extremely helium-rich stars. It was also noticed that the pulsator population tends to increase with the decrease in helium content. The study was enhanced by discussing the kinematic properties of 1640 subdwarfs in the context of their Galactic population membership. Most of those stars were found to belong to the thin and thick disc populations. Interestingly, more p-mode pulsators were found in the halo population, which is an original and important result but still preliminary due to the limited sample used. My only critical comment: readers could wonder why observations from individual years were analysed separately. Wouldn't Fourier analysis of combined light curves provide more frequencies?

Papers IV and V focus on determining the astrophysical properties of individual pulsating hot subdwarfs. The results of these studies constitute the original and essential contributions to the subject matter. As the databases grow, the statistical analyses become more robust, allowing more subtle relations to be identified. Such an attempt was made in paper V, resulting in the preliminary detection of the original relations.

The contribution statements of S. K. Sahoo and the co-authors of the papers clearly show that his role was leading. He is the first author of 4 articles, and his contribution included data reduction and analysis, discussing the results, and writing and editing the manuscript. The presented descriptions of the individual stages of the research work clearly show that the analysis process was carried out correctly and reliably from the methodological point of view. It is worth emphasising that S. K. Sahoo collaborated with scientists from many institutions, proving he has above-average teamwork and team-leading skills. Thus, there is no doubt that the PhD candidate can independently conduct further scientific work.

3. Summary

The doctoral thesis submitted by Sumanta Kumar Sahoo is undoubtedly an original solution to a well-defined scientific problem. Thanks to the significant increase in the number of catalogued sdB pulsating stars, which remain relatively poorly studied, it becomes possible to analyse their population properties in the Milky Way. The content of the dissertation proves that the PhD student has mastered the subject knowledge at an expert level. Moreover, he has demonstrated an above-average ability to solve research problems. Accounting for the elements mentioned above, I consider the doctoral thesis of Sumanta Kumar Sahoo to be **outstanding** with a valuable scientific contribution, meeting all the criteria prescribed by Article 187 of the Act *Prawo o szkolnictwie wyższym i nauce*[1]. Therefore, I request that this dissertation be admitted to public defence.

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[1] Ustawa z dnia 20 lipca 2018 r. „Prawo o szkolnictwie wyższym i nauce", Dz.U. z 2018 r., poz. 1668 z późn. zm.