Evolved compact stars in the era of photometric space missions

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Closing report

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Introduction

This PD project aimed at the better understanding of compact pulsators (white dwarf and hot subdwarf stars), utilizing ground- and space-based (*TESS* – Transiting Exoplanet Survey Satellite) observations.

White dwarfs represent the final evolutionary stage of stars with low-to-intermediate initial mass, comprising $\sim 97\%$ of all stars, including our Sun. Some of the white dwarfs show low-amplitude short-period light variations due to oscillations. We can find them in well-defined regions of the Hertzsprung–Russell-diagram, and they are classified in three major groups: GW Vir, V777 Her (DBV) and ZZ Ceti (DAV) stars. Compact pulsators are also found among objects being in post-Red Giant Branch (RGB) evolutionary phases, on the so-called Extreme Horizontal Branch (EHB), and beyond. These are the **hot subdwarf stars** (referred to as sdB, sdOB or sdO stars, depending on their spectral type). Some of these objects also show pulsational light variations. **The proven sensitivity of the excited periods to the global stellar structure, rotation, internal chemical stratification and dynamics shows their great potential for asteroseismic studies**, and thus investigations of both the pulsating white dwarf and hot subdwarf stars are essential for understanding the late stages of stellar evolution.

The *TESS* space telescope was launched successfully on 18 April 2018 as part of NASA's Explorer program. The main goal of this all-sky survey space mission is to detect exoplanets with the transit method. However, with the 30-min full-frame sampling, and with the 120-sec short-cadence sampling of selected targets, *TESS* is also suitable for studying the light variations of variable stars, including short-period compact pulsators. The related scientific activities are coordinated by the *TESS* Asteroseismic Science Consortium (TASC) "Evolved compact stars with *TESS*" Working Group (WG8). **This project enabled the principal investigator (PI) to play a dynamic and recognised role in the efforts of TASC WG8.**

During this PD project, the PI took part in the publication of several scientific papers, both in high-impact-factor refereed journals and conference proceedings. She first-authored **5** papers, including **1** conference proceedings, while she contributed as co-author to the preparation of **11** additional papers (including **1** conference proceedings).

1 *TESS* pre-launch activities

The PI joined in the finalisation of the of the WG8 prioritised target lists, and thus **become one of the co-authors of the WG8 "first-light" *TESS* paper [11]**. That is, the PI participated in the completion of *TESS* observing proposals for the 20 sec and 2 min cadence measurements (S. Charpinet, E.M. Green, S. Geier, D. Kilkenny, Zs. Bognár, J.J. Hermes, S. Murphy, et al.: "High precision monitoring of fast photometric variability in evolved compact stars with *TESS*", "*TESS* all sky variability survey for evolved compact stars"), and recommended the observation of 11 ZZ Ceti stars and 1 hot DAV in 20 sec-cadence mode, which were added to the prioritised target list of the application.

2 Analysis of *TESS* data

According to the Workplan of this PD project, the PI participated in the analysis of *TESS* data on compact variables. She complemented this work with the investigation of *TESS* data on other types of pulsating variables (roAp and delta Scuti stars).

2.1 Compact variables

- **The PI led the investigations of the 18 known ZZ Ceti stars observed by *TESS* during the first observing cycle** (southern ecliptic hemisphere, sectors 1–13), **and was the leading author of the corresponding ZZ Ceti "first-light" paper** [16].

  We focused on the frequency analysis of the space-based observations, comparing the results with findings of previous ground-based measurements. The frequencies detected by the *TESS* observations can serve as inputs for future asteroseismic analyses, which were decided to be presented in a separate paper [Romero et al., in prep.].

  We detected **more than 40 pulsation frequencies** in seven ZZ Ceti stars observed with 120 s cadence by *TESS*, with precision better than 0.1 μHz. We demonstrated the difference between the *TESS* amplitudes and those measured in the ground-based observations through the example of Ross 548. We detected new frequencies in five stars (EC 23487-2424, BPM 31594, BPM 30551, MCT 0145-2211, and HS 0507+0434B).

In contrary to the results of the previous ground-based measurements, we found no significant periodicities detected in HE 0532-5605 in the complete *TESS* data set. However, we found that **HE 0532-5605 may be a new outbursting ZZ Ceti star**, as close examination of the sector 1 light curve suggests that a burst (increase in the stellar flux in cool ZZ Ceti stars) may have occurred at about BJD 2 458 340 (8 August 2018). The possible burst reached an amplitude of nearly 20% of the stellar luminosity, and its duration was approximately 24 hours.

We detected **rotationally split triplet frequencies** in several stars, which can be used to derive the stellar rotation rates of these objects.

We also found possible **amplitude or phase variations** during the *TESS* observations, which resulted in the emergence of groups of peaks in the data sets of EC 23487-2424, BPM 30551, and MCT 0145-2211. We fit Lorentzians to these frequency groups to approximate the pulsation frequencies. Such behaviour in these stars had not been identified from the ground before, however, this phenomenon is in agreement with the expected behaviour of pulsation modes in the long-period regime above $\sim$800 sec.

Ten targets do not show any significant pulsational light variations, due to a combination of their intrinsic faintness and/or crowding on the large *TESS* pixels.

- **The PI participated in the frequency analyses of data sets on certain compact pulsators**: the DBV star TIC 257459955 [10], and the DOV star TIC 3905338 [paper in prep., Sowicka et al.]. The related papers are the "first-light *TESS* papers" of the given type of objects.

- In the case of the data obtained during the first four observing sectors of *TESS*, **the PI took part in the classification of data sets** observed at different sectors considering the characteristic of the light curves: they were classified as stars showing evidence of pulsations, other kinds of variability (rotation, binarity, etc.), no variability, or only instrumental signals. The results were summarised in the TASC WG8 webpage[1].

2.2 Other objects

The PI joined in the analysis of *TESS* data sets of roAp and delta Scuti stars, with independent frequency analyses of some of the targets, and literature search. This work resulted in co-authorship in two papers so far [9][12].

[1]https://tasoc.dk/wg8/ – for registered TASC members only

3 Ground-based observations of compact variables

The PI led an observing survey with the aim to find new white dwarf pulsators for observations by *TESS*. For this purpose, we collected photometric time-series data on 21 white dwarf variable-candidates at the Piszkéstető mountain station of Konkoly Observatory during the 2017 March – 2018 July term. The 21 targets were bright DA and DB white dwarfs located close to the empirical DA and DB instability strips, respectively. We looked for new pulsators amongst white dwarfs brighter than 16.5 magnitude.

We successfully identified a variable candidate (EGGR 120), **two new pulsators**, WD 1310+583 and PM J22299+3024, and derived detection limits for possible pulsations for 18 objects [3][8][13].

We also performed extended observations of two other proposed *TESS* targets, LP 119-10 and HS 1625+1231, respectively.

Additionally, we identified three new variable stars in the fields of our white dwarf targets: an eclipsing binary, a candidate delta Scuti/beta Cephei, and a candidate W UMa-type star.

Altogether, we collected data in the 1 September 2017 – 31 August 2020 term on **117** nights.

3.1 Analysis of archive white dwarf data

We summarised our findings on three ZZ Ceti stars close to the red edge of the DAV instability strip, observed earlier at Piszkéstető mountain station [7]. We detected eight independent modes in the sparsely observed HS 0733+4119, of which seven are new findings. For the relatively well-studied target, GD 154, we detected two new eigenmodes at 798.3 and at 1130.5 μHz, and confirmed the recurrence of the exceptional pulsational behaviour first observed in 1977. Similarly to that previous observation, one mode and its harmonic and near-subharmonic peaks dominated the light variations of the star in our data during this period. We also discussed the differences between its pulsational behaviour observed in different epochs: GD 154 does not only alter its pulsations between a multiperiodic and a quasi-monoperiodic phase, but there are also differences between the relative amplitudes of the near-subharmonics in the latter phase. In the case of Ross 808, which is a pulsator rich in frequencies that result in complex light variations, we compared the pre- and post Whole Earth Telescope campaign measurements, and determined two new frequencies besides the ones observed during the campaign.

4 Asteroseismology

In the case of the ZZ Ceti star discovered by our team, WD 1310+583, **the PI performed asteroseismic investigations** utilising a previous version (Bischoff-Kim et al. 2008) of the White Dwarf Evolution Code (WDEC). However, in the meantime, a new version of the WDEC has been published

(Bischoff-Kim & Montgomery 2018). This updated version uses MESA (Modules for Experiments In Stellar Astrophysics) equation of states and opacities routines and enables a more sophisticated parametrisation of the models than the previous version she used. During the second year of the PD project, the PI got acquainted with the new code by performing several experimental runs to discover the effects of the different parameters on the resulting goodness of asteroseismic fits, and utilised the new code for the asteroseismic investigations of PM J22299+3024 and LP 119-10.

4.1 WD 1310+583

We successfully observed WD 1310+583 on eight nights, and determined 17 significant frequencies in the whole data set. Seven of them appear to be independent pulsation modes between 634 and 2740 μHz. We performed preliminary asteroseismic investigations of the star utilising six of these periods.

The additional, closely spaced frequencies to these modes suggest the presence of amplitude and/or phase variations, frequently observed in ZZ Ceti stars in the middle of the instability strip or close to its red edge. This newly discovered relatively bright WD variable is an excellent target for 1-m-class telescopes.

We found, that utilising our model grid, the best-fitting model has a stellar mass higher than that determined by optical spectroscopy, but its effective temperature is close to the value calculated from the optical spectrum. However, note that in this case the dominant mode is $\ell = 2$. Assuming that at least four of the modes is $\ell = 1$ (including the dominant frequency), considering the better visibility of $\ell = 1$ modes over $\ell = 2$ ones, the best-fitting model has $T_{\rm eff} = 11\,600\,$K and $M_* = 0.74\,M_\odot$. This solution has stellar mass close to the value determined by optical spectroscopy, but its effective temperature fits better to the value calculated from a far-ultraviolet (FUV) fitting. We tried another fit adding the two frequencies found by Gentile Fusillo et al. (2018), that is, we fitted eight periods with the calculated ones. In this case, the best-fitting model has $T_{\rm eff} = 11\,900\,$K and $M_* = 0.80\,M_\odot$. This is also the best-fitting model assuming that at least five of the modes is $\ell = 1$. Considering the effective temperatures of the best-fitting models, they seem to confirm the higher value determined by FUV observations. The relatively large amplitude pulsations also support the idea that WD 1310+583 may be closer to the middle of the ZZ Ceti instability strip, than it is at the red edge.

4.2 PM J22299+3024

We discovered the variability of PM J22299+3024 in July 2018. At that time we referred to it as a variable candidate, as only one night of observations was available on this target [8]. However, the follow-up observations confirmed that PM J22299+3024 is indeed a new, bright ZZ Ceti pulsator, situated close to the red edge of the instability strip. Based on 14 nights of observations (2018 July–November), we accepted six modes, which were inputs for asteroseismic fittings. However, its complex frequency structure suggests that further modes may be present in the data set. The observed amplitude variations of the frequencies from one observing week to another made the determination of these additional frequencies ambiguous. We obtained data on PM J22299+3024 on six night in the 2019 observing season, too, and we used these measurements to check if we can find the frequencies determined by the 2018 data set in these new data.

Note that the star was amongst the targets proposed for *TESS* observations. However, because of the unexpected field shifts, the space telescope did not observe PM J22299+3024 so far. This was one of the main reasons, why we decided to collect more data on this target from the ground in 2019.

Assuming that at least half of the observed modes is $\ell = 1$, the best-fitting model has $T_{\rm eff} = 10\,600\,{\rm K}$ and $M_* = 0.49\,M_\odot$, which is in good agreement with the values obtained by optical spectroscopy ($T_{\rm eff} = 10\,630 \pm 155\,{\rm K}$ and $M_* = 0.46 \pm 0.03\,M_\odot$).

4.3 LP 119-10

LP 119-10 was discovered to be a variable star by Green et al. (2015). We collected data on this star altogether on 20 nights between October 2018 and April 2019. Our data analysis revealed an even more complex frequency structure than in the case of PM J22299+3024, and we have determined 7 pulsation modes between 765 and 978 s.

Fortunately, *TESS* also observed the star in the 28 November – 23 December, 2019 period (sector 19). We were able to determine further three significant frequencies from this data set.

We performed asteroseismic fits both utilising the ground-based frequencies and the frequency list completed with the three additional frequencies obtained by the *TESS* measurements. Interestingly, in the case of the 7-frequency solution, the best-fitting model ($T_{\rm eff} = 10\,800\,{\rm K}$ and $M_* = 0.64\,M_\odot$) is a bit cooler than we expect from optical spectroscopy ($T_{\rm eff} = 11\,290 \pm 170\,{\rm K}$ and $M_* = 0.65 \pm 0.03\,M_\odot$), but with a mass very close to the expected value. In this case we assumed that at least 4 of the modes are $\ell = 1$ out of the 7 observed. However, adding the three *TESS* frequencies to the period list, and assuming that at least half of the 10 modes are $\ell = 1$, we obtain completely different best-fitting solutions with relatively high temperatures and masses around $T_{\rm eff} = 11\,800\,{\rm K}$ and $M_* = 0.71 - 0.74\,M_\odot$. The PI is still working on the asteroseismic analysis of this star, to find the explanation of this discrepancy.

Thus, the corresponding paper presenting the observational and asteroseismic analysis of the two stars PM J22299+3024 and LP 119-10 is still in preparartion at the time of writing of this report, but intended to be submitted to Astronomy and Astrophysics during the autumn of 2020 [17].

5 Other activities

- Spectroscopic observations of Kepler delta Scuti–gamma Doradus hybrid candidate variable stars at Konkoly Observatory to determine the binary ratio among them in an international collaboration. The corresponding results were published in a referred journal [1]. Another publication on this project is under referee review at the time of writing this report, and expected to be accepted in 2020 [18].

- Participation in the analysis of the data collected during a multisite observing campaign on the delta Scuti star 38 Eri. My task was to give constraints on the pulsation modes' horizontal degree (ℓ) number utilising the Fourier parameters obtained from different bandpass light curves. The results were published in Monthly Notices of the Royal Astronomical Society [2].

- Participation in the observing campaigns of the supernovae SN 2018oh and SN 2018cow, respectively. Two papers with my co-authorship have been published already in Astrophysical Journal on SN 2018oh [4][5].

- We reported on the analysis of 34 years of photometric observations of the pulsating helium atmosphere white dwarf GD 358. I participated in the data reduction during one of the Whole Earth Telescope campaigns on this target [6].

- The PI of this PD project was also the principal investigator of a successful proposal submitted for requiring observations with the BRITE Constellation satellite mission of the planet hosting gamma Doradus star HR 8799. Finally, BRITE observed this target in 2017 for 140 days, and we presented the results of the frequency analysis of this space-based data [14].

- We presented the first data release of photometric analysis of *TESS* observations of small solar system bodies, focusing on the bright end of the observed main-belt asteroid and Jovian Trojan populations [15]. I joined in the characterisation of the resulting light curves.

6 Other results of project

The following prizes and grants were awarded to the PI during the reporting period:

- **Young Researcher Award** of the Hungarian Academy of Sciences (2020)

- **János Bolyai Research Scholarship** of the Hungarian Academy of Sciences (2020–2023)

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