HABILITATION SUMMARY

1. Name: **Radosław Smolec**

2. List of all scientific degrees (including name, place, and date of obtaining; PhD thesis title):

   a) Master of Science (MSc), speciality: astronomy, University of Warsaw, 17.06.2004; title. "*Metaliczność gwiazd RR Lutni a Efekt Błażki*", supervisor prof. dr hab. Paweł Moskalik

   b) Doctor of Philosophy (PhD) in astronomy, Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences, Warsaw, 25.09.2009; thesis title "*Nonlinear Modeling of Radial Stellar Pulsations*", supervisor prof. dr hab. Paweł Moskalik

3. Employment

   a) Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences, Warsaw, 2012–
   teanure-track, 2015–
   post-doc, 2012–2015

   b) Institute of Astronomy, University of Vienna, Vienna, Austria
   post-doc, 2009–2011

4. Habilitation achievement:

   a) title

Dynamical phenomena in the models and observations of classical pulsating stars

   b) author(s), title(s) of publications, year of publishing, journal name

- **H1**. Smolec, R., Soszyński, I., Moskalik, P., Udalski, A., Szymański, M.K., Kubiak, M., Pietrzyński, G., Wyrzykowski, Ł., Ulaczyk, K., Poleski, R., Kozłowski, S., Pietrukowicz, P., *Discovery of period doubling in BL Herculis stars of the OGLE survey. Observations and theoretical models*, 2012, Monthly Notices of the Royal Astronomical Society, **419**, 2407–2423
- **H2**. Smolec, R., Moskalik, P., *Period doubling and Blazhko modulation in BL Herculis hydrodynamic models*, 2012, Monthly Notices of the Royal Astronomical Society, **426**, 108–119
- **H3**. Smolec, R., Moskalik, P., *Chaos in hydrodynamic BL Herculis models*, 2014, Monthly Notices of the Royal Astronomical Society, **441**, 101–115
- **H4**. Smolec, R., Soszyński, I., Udalski, A., Szymański, M.K., Pietrukowicz, P., Skowron, J., Kozłowski, S., Poleski, R., Skowron, D., Pietrzyński, G., Wyrzykowski, Ł., Ulaczyk, K., Mróz, P., et al. *Blazhko-type modulation in the double-mode RR Lyrae stars of the OGLE Galactic bulge collection*, 2015, Monthly Notices of the Royal Astronomical Society, **447**, 3756–3774

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- **H5**. Smolec, R., *Survey of non-linear hydrodynamic models of type-II Cepheids*, 2016, Monthly Notices of the Royal Astronomical Society, **456**, 3475–3493
- **H6**. Smolec, R., Śniegowska, M., *Non-radial pulsation in first overtone Cepheids of the Small Magellanic Cloud*, 2016, Monthly Notices of the Royal Astronomical Society, **458**, 3561–3577

c) presentation of research goals, results and resulting publications

Introduction – classical pulsating stars

Classical pulsating stars are large amplitude periodic variables. Their brightness changes are mostly due to radial oscillations driven by the opacity mechanism in the partial hydrogen-helium ionization zones (e.g. Cox, 1980). In the Hertzsprung-Russell (HR) diagram, they are located within the so-called classical instability strip. The group consists of

• classical Cepheids (population I) – young, massive and metal rich stars, that cross the classical instability strip either after hydrogen depletion in the core, while evolving fast towards the red giant branch, or during the core-helium burning (blue loop in the HR diagram).

• RR Lyrae stars, old, low-mass and typically metal poor stars. After helium ignition in the core, they slowly evolve within the classical instability strip away the Zero-Age Horizontal Branch (ZAHB).

• Population II Cepheids (also type II Cepheids); with physical parameters similar to RR Lyr stars. After helium ignition in the core, they arrive at the blue part of the ZAHB and cross the instability strip at higher luminosities (and longer periods) than RR Lyr stars. The group is divided into three classes, depending on the pulsation period and evolution stage: BL Her stars ($1 \lesssim P \lesssim 4$ d), W Vir stars ($4 \lesssim P \lesssim 20$ d) and RV Tau stars ($P \gtrsim 20$ d). In RV Tau stars, characteristic alternations of deep and shallow minima/maxima in the light curve, the so-called period doubling effect, are observed.

Classical pulsators are of great astrophysical importance. They serve as distance indicators, as their absolute luminosity can be determined through the period-luminosity ($P-L$) relation. Classical Cepheids are one of the most important rungs in the cosmic distance ladder. Population II Cepheids, due to lower luminosities and not that well defined $P-L$ relation, are used less often. RR Lyr stars are invaluable in the studies of structure, kinematics and chemical evolution of the nearby stellar systems.

Classical pulsators are very interesting also from dynamical point of view, as they display a wealth of pulsation forms and patterns. Although single-periodic oscillations in the radial modes, radial fundamental (F) or radial first overtone (1O), dominate, multi-mode pulsation is not rare. We observe both radial multi-mode pulsators as well as pulsation with non-radial modes excited. Of particular interest are resonant effects between pulsation modes, which may lead to phenomena like bump progression, period doubling or multi-mode pulsation. The Blazhko effect, a quasi-periodic modulation of pulsation amplitude and/or phase observed in a significant fraction of RR Lyr stars, is very puzzling. The mechanism behind the Blazhko modulation remains unknown. The just indicated dynamical phenomena are in the center of my scientific interests, starting from my first publication, in which the metallicity dependence of the Blazhko effect was studied (Smolec, 2005), till the most recent paper, in which properties of the non-radial modes excited in first overtone Cepheids were studied (Smolec & Śniegowska, 2016).

Better understanding of dynamical phenomena that occur in classical pulsators, requires extensive and top-quality observations of these stars and in-depth analysis of these observations. Comprehensive knowledge of observational properties of these phenomena, including e.g. their population dependencies, is necessary to propose and test the models explaining the mechanisms underlying the observed variations. An excellent source of such observations are photometric sky surveys, like the Optical Gravitational Lensing

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Experiment (OGLE, e.g. Udalski, Szymański & Szymański, 2015), operating for nearly 25 years now. Recently, photometric data of unprecedented quality are collected by space telescopes, *Kepler* and *CoRoT*.

In **H4**, an in-depth analysis of the OGLE observations for RR Lyr stars showing the newly discovered phenomenon, the Blazhko effect in double-mode variables, is presented. In **H6** double-mode classical Cepheids, with radial and non-radial modes excited, are analysed. The analysis strongly supports a recent model in which identification and excitation mechanism for these modes is proposed. The remaining four papers in the habilitation achievement are of theoretical nature. In **H1** results of modelling of the first BL Her star showing period doubling effect are presented. Other two papers are dedicated to in-depth study of two intriguing phenomena detected in the models of BL Her-type stars, quasi-periodic modulation of pulsation (paper **H2**) and deterministic chaos (paper **H3**). In the last paper, **H5**, an extensive survey of Population II Cepheid models is presented, indicating that new dynamical phenomena might be present in these stars and await discovery.

In four papers the pulsation codes are used as basic research tool. These codes were largely written by myself, as part of my PhD project. Therefore, in the next section, more detailed description of these codes is provided, in particular of their aspects relevant for the studies discussed later on.

Tools for modelling stellar pulsation

In 2004 I started PhD studies at the Nicolaus Copernicus Astronomical Center, supervised by prof. dr hab. Paweł Moskalik. The goal of the proposed research project was non-linear modelling of double-mode Cepheids, preceded by the development of necessary tools – non-linear convective pulsation codes.

First pulsation codes suitable for realistic modelling of light and radial velocity curves were developed in the sixties (e.g. Christy, 1966). Such codes usually consist of three independent subroutines. The first subroutine constructs static equilibrium (envelope) model of a star. The next subroutine conducts linear non-adiabatic stability analysis. As a result one gets pulsation periods of the possible oscillation modes and their linear growth rates. The growth rates determine whether the pulsation mode is self-excited or damped. In the last, non-linear code, the static model is used as a starting point for non-linear model integration. The static model is perturbed and equations of hydrodynamics are followed till model settles on finite-amplitude pulsation. Various forms of pulsation are possible, e.g., single-periodic limit cycle, stable double-mode pulsation, modulated oscillations or chaotic oscillations.

The non-linear pulsation codes described here are one-dimensional and allow the modelling of radial pulsation only. The first codes were also purely radiative; the convective energy transfer in the envelope was neglected. The radiative code that was most extensively used in the study of classical pulsators was developed by Stellingwerf (1975). Unfortunately, with the radiative pulsation codes modelling of double-mode pulsation was not possible. The first turbulent convection model suitable for non-linear pulsation codes was proposed by Stellingwerf (1982). This model is used in the pulsation code developed by the Italian group (e.g. Bono & Stellingwerf, 1994). Unfortunately, with the Stellingwerf's convection model double-mode pulsation cannot be modelled, just as in the radiative case. A slightly different model of convection was proposed by Kuhfuß (1986). Implementation of this model into the so-called Florida-Budapest code finally led to success. Stable double-mode pulsation models both for Cepheid and for RR Lyr models were computed (e.g. Kolláth et al., 2002). Consequently, it was the Kuhfuß (1986) model that was selected for implementation in the Warsaw codes I was developing. The codes are based on radiative Stellingwerf (1975) codes. Inclusion of turbulent convection forced significant rewriting of the codes, in particular of the model builder and linear stability analysis subroutines. Unfortunately, with the new, non-linear, convective pulsation code, stable double-mode pulsation could not be computed, despite the Kuhfuß model was implemented. Detailed investigation (Smolec & Moskalik, 2008b, PhD thesis[1]) pointed that the Florida-Budapest codes implement modified Kuhfuß model, in which buoyant force is neglected in the convectively stable regions. With such assumption, the numerically demanding sharp gradients of turbulent energy are softened. Nevertheless, neglect of buoyant force in the convectively stable regions is unphysical and has severe consequences for the models. Among these are the extreme extent of convective overshooting and appearance of the double-mode pulsation. With the correct treatment of the buoyant force, stable non-resonant double-mode pulsation cannot be computed. It is also the case for the Stellingwerf's convection model implemented in the Italian code.

Despite modelling of stable, non-resonant, double-mode pulsation of Cepheids and RR Lyrae stars is not possible with the present pulsation codes, it is hard to overestimate their capabilities. The codes are excellent tools for modelling of single-periodic stars, of resonant phenomena (e.g. bump progression, period doubling, resonant double-mode pulsation) and of other dynamical effects (modulated pulsation, deterministic chaos).

The Kuhfuß model is relatively simple, one-dimensional model, in which the generation of turbulent energy is described with one equation. The simple form of the model enables its use in the non-linear pulsation codes. On the other hand, this form is achieved at the cost of some simplifying assumptions. As a result, quantities, such as convective or turbulent fluxes, turbulent pressure, etc., are determined up to a scaling factor. The Kuhfuß model contains 8 such parameters. For some of them the so-called standard values are in use, which result from comparison of the static version of the model with the standard mixing-length theory. In practice, these are free parameters, values of which should be calibrated to reproduce as many observational constraints as possible. The universal calibration is not possible, however. The properties of turbulent convection are most likely different in different groups or classical pulsators, or even within a single group. The model describes the phenomena that are complex, essentially three-dimensional, and occur over a range of time scales and spatial scales, in a strongly simplified way. Hence, parametric studies, in which the effects of some particular model parameter on the properties of the pulsation model are investigated, are very important. Such studies (also described below) reveal that the dynamical properties of the pulsation models depend most significantly on the amount of eddy-viscous dissipation in the model, controlled by the eddy-viscosity parameter, α_{m}. This is also well known from the purely radiative models, in which a similar role is played by the so-called artificial viscosity (e.g. Kovács & Buchler, 1988a).

[1]Available at http://users.camk.edu.pl/smolec/phd_smolec.pdf.

Dynamical phenomena in the models and observations of classical pulsating stars

The hydrodynamic models of pulsating stars sometimes display a behaviour that is not observed in stars. In a sequence of radiative hydrodynamic models of BL Her-type stars, with periods in the $2<P<2.6$ d range, Buchler & Moskalik (1992) detected a period doubling behaviour. This phenomenon is well known in longer-period, RV Tau stars, but not in BL Her stars. Period doubling phenomenon is caused by the half-integer resonances between the radial pulsation modes, as first shown by Moskalik & Buchler (1990). In RV Tau stars the 5:2 resonance, $5\nu_{\rm F}=2\nu_{\rm 2O}$, is crucial, while in the radiative BL Her models of Buchler & Moskalik (1992) the 3:2 resonance, $3\nu_{\rm F}=2\nu_{\rm 1O}$, is operational. The phenomenon was detected in a few model sequences; its presence was not sensitive to the details of numerical modelling (such as e.g. time step or grid resolution). Consequently, Buchler & Moskalik (1992) concluded that period doubling effect should be present in some BL Her stars. At that time the observations of Population II Cepheids were rather scarce and of poor quality. The situation has changed with the regular monitoring of large sky areas by the OGLE project. One of 156 BL Her stars identified in the OGLE observations of the Galactic bulge shows the period doubling effect (Soszyński et al., 2011b). It is OGLE-BLG-T2CEP-279 (T2CEP-279, in the following) and its pulsation period, $P\approx 2.4$ d, well fits into the range predicted by Buchler & Moskalik (1992). Other BL Her star is a candidate with a likely, but less pronounced effect. Detailed investigation and modelling of T2CEP-279 was conducted in **H1 (Smolec et al., 2012)**[2]. The analysis of observations was done by prof. dr hab. Paweł Moskalik, while I was responsible for the modelling of the star. The goals of the modelling were the following. (*i*) Modelling of the period doubling effect with the convective pulsation code including up-to-date microphysics data[3]. (*ii*) Investigation of the mechanism behind the period doubled-pulsation, in particular, verification whether the role of the 3:2 resonance remains crucial in the convective models. (*iii*) Attempt to constrain the physical parameters of T2CEP-279 by modelling of its light curve.

The calculations were conducted for a grid of models of different masses ($M=0.50$, 0.55, 0.60, 0.65 $\mathrm{M}_\odot$) and of different metallicities ($Z=0.01$, 0.001, 0.0001). All models were computed along a line of constant period, equal to the pulsation period of T2CEP-279, $P\approx 2.4$ d, with the $2\,\mathrm{L}_\odot$ step in absolute luminosity. For each combination of M and Z, models in some luminosity range show the period doubling alternations. For these and other models, linear stability analysis allows to compute the period ratios of the radial modes and hence, allows to check how far the period doubled models are from centers of various resonances. The analysis leaves no doubt; it is the 3:2 resonance between the fundamental mode and the first overtone that is responsible for the computed period doubling behaviour, just as in the case of radiative models.

Models with period doubling effect have different amplitudes of pulsation and of alternations. Comparison with the observed amplitudes led to the selection of three models with light curves that match the T2CEP-279 light curve best. These models and their

[2] Paper **H1** was finished just before the period doubled star got its official name, assigned in the XIV part of the OGLE catalog (Soszyński et al., 2011b). In **H1** it has the following identifier, BLG184.7 133264.

[3] In the early nineties, a significantly revised opacity tables were published (Iglesias & Rogers, 1991), which strongly influence the pulsation properties of the models.

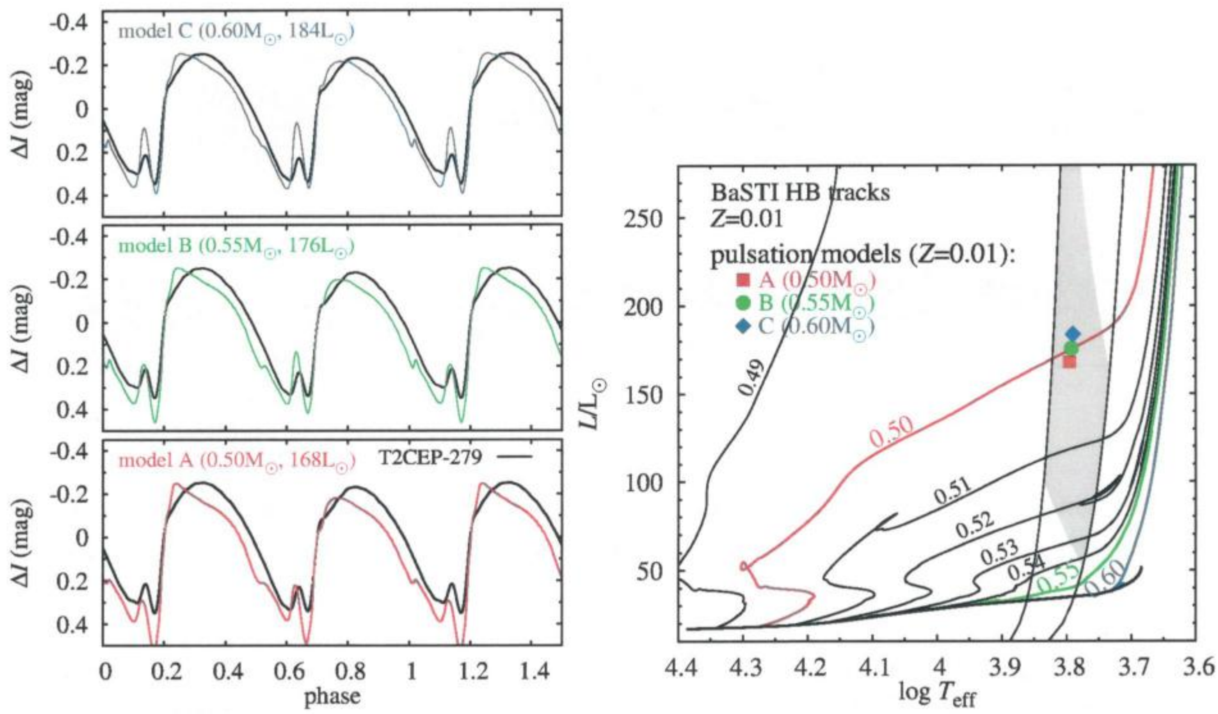

Figure 1: Modelling for T2CEP-279. In the left panels, light curves for three best models are plotted and compared with the observed light curve (solid black line). The right panel shows the location of these models in the HR diagram and comparison with the BaSTI stellar evolution tracks (Pietrinferni et al., 2006). Tracks are labelled with the mass values. The BL Her domain is marked as grey-shaded area within the classical instability strip.

comparison with observations are presented in the left panel of Fig. 1. The three models have the same, high metallicity, $Z = 0.01$, but different masses. In the HR diagram they are located at nearly the same place as illustrated in the right panel of Fig. 1. Hence, it is possible to constrain the model parameters further, with the help of the stellar evolution tracks, which are strongly sensitive to model's mass. A comparison, presented in the right panel of Fig. 1, clearly shows that only the least massive model is compatible with stellar evolution calculations.

The analysis done in **H1** is a kind of non-linear asteroseismic modelling of the star. T2CEP-279 is in fact a double-mode star, due to the half-integer resonance. The resonance is responsible for the characteristic, period-doubled shape of the light curve. Modelling of the light curve led to the estimation of star's physical parameters. Paper **H1** demonstrates the predictive power of the non-linear pulsation theory. Presence of some particular phenomenon in the hydrodynamic models, that is not observed in stars, not necessarily indicates that the model parameters or the underlying physics are not correct. The phenomenon may be rare and/or its discovery requires top-quality and long monitoring of stars' variability. With this thought in mind, two additional papers on BL Her models, discussed below, were published.

While checking the effects of different values of convection model's parameters on the shape of the computed light curves and on the existence of period doubling effect, two very interesting forms of pulsation were detected. When eddy viscosity parameter was

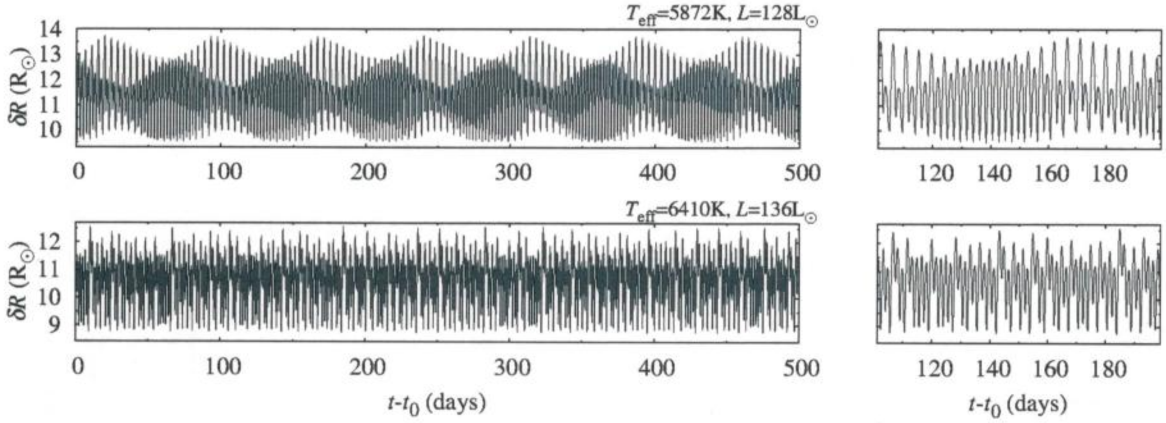

Figure 2: Radius variation curves for two exemplary models (*top panel*): showing periodic modulation of pulsation on top of period doubling effect (paper **H2**) and (*bottom panel*): showing deterministic chaos (paper **H3**). In the right panels the zoom-ins are plotted.

significantly lowered, depending on model's location in the HR diagram, two dynamical phenomena were computed: periodic modulation of pulsation and deterministic chaos. These phenomena were not observed in BL Her stars yet. Their detailed analysis was presented in **H2** and in **H3**.

In **H2 (Smolec & Moskalik, 2012)** several sequences of BL Her-type models, in which quasi-periodic modulation of pulsation on top of period doubling effect is present, are analysed. The model sequences are of constant luminosity, in the $120 - 160\,\mathrm{L}_\odot$ range. All models are of the same mass ($0.55\,\mathrm{M}_\odot$) and chemical composition ($X = 0.76$, $Z = 0.0001$). Radius variation in exemplary model is plotted in the top panel of Fig. 2. Detailed analysis of the return maps shows, that in some models the modulation is of chaotic character, but the dominant variability may be well described as quasi-periodic.

The dynamical behaviour detected in the models is qualitatively similar to the Blazhko effect observed in RR Lyr stars pulsating in the fundamental mode. The period doubling effect in several of these stars was discovered only recently, thanks to precise and nearly continuous observations of the *Kepler* space telescope (Kolenberg et al., 2010). Period doubling was detected only in RR Lyr stars showing the Blazhko modulation. Hence, Buchler & Kolláth (2011) proposed a model in which these two phenomena: period doubling and modulation of pulsation are connected. In this model, period doubling behaviour is caused by the 9:2 resonance between the fundamental mode and the ninth overtone. The latter mode is special: it is a surface (or trapped) mode with high oscillation amplitude only above the partial hydrogen ionization regions. Using the amplitude equations formalism, Buchler & Kolláth (2011) showed, that the 9:2 resonance can also cause the modulation of pulsation, which is periodic or chaotic. Reliance of the model on amplitude equations is its weakest point. The form of the solution of the amplitude equations depends on the values of several coefficients: cross- and self-saturation coefficients and resonant coupling coefficients. Their calculation for the discussed case is too complex and hence some *ad hoc* values were used (which is common approach in the analyses of amplitude equations). Calculations of Buchler & Kolláth (2011) show, that the modulation of pulsation is a possible solution of the amplitude equations, but do not prove that such mechanism indeed works in the stars. A much stronger evidence can be provided by hydrodynamic modelling. Unfortunately, hydrodynamic models of RR Lyr-type stars do not show the modulation of pulsation. Some models show the period doubling effect, but no modulation (Kolláth, Molnár & Szabó, 2011; Smolec, 2015). It may be a consequence of very difficult modelling of the surface mode crucial in this scenario – high order radial overtone. In this context, the results presented in **H2** are very important. It is shown that the mechanism proposed by Buchler & Kolláth (2011) may indeed work in the hydrodynamic models of BL Her stars, a more luminous siblings of RR Lyr stars. The pronounced modulation in these models, observed on top of period doubling effect, is caused by the half-integer resonance, just as in the Buchler & Kolláth (2011) model. The resonance is just of lower order; it is the 3:2 resonance between the fundamental mode and the first overtone. It is the same resonance that causes the period doubling effect in T2CEP-279. The results of hydrodynamic modelling are qualitatively reproduced with the analysis of appropriate amplitude equations.

The periodic modulation of pulsation was not discovered in BL Her stars yet. However, the hydrodynamic models and analysis of amplitude equations clearly point, that such form of pulsation is possible. It may be very rare, just as in the case of period doubling effect. I hope that this interesting form of pulsation will be detected in stars soon.

Irregular oscillation is typical for longer period Population II Cepheids or for Mira type or semi-regular variables. The deterministic chaos may underlie the observed variability; however, long, regular and precise observations are necessary to prove the presence of chaos. Only for a few stars the observations were good enough to conduct the relevant tests which confirmed the presence of chaotic dynamics (see e.g. Buchler, Kolláth & Serre, 1996; Kolláth et al., 1998). On the modelling side, chaos was detected in the radiative models of W Vir and RV Tau type stars calculated by Kovács & Buchler (1988b). Chaos in these models appeared either through the period doubling route or as a result of the tangent bifurcation. In **H3 (Smolec & Moskalik, 2014)** the chaotic dynamics is analysed in the sequence of BL Her-type models with reduced eddy viscosity. It is demonstrated, for the first time, that the full wealth of dynamic behaviours, well known from textbook chaotic systems (e.g. Lorenz system, Rossler system, logistic map), is possible in the hydrodynamic models of stars. Many of these phenomena were never considered in the context of pulsating stars before.

To fully map the domain of the phase space occupied by the chaotic attractor, it is necessary to compute several thousands of pulsation cycles for each model, which is numerically demanding. Consequently, the study presented in **H3** was limited to one sequence of models of constant mass ($0.55\,\mathrm{M}_{\odot}$), chemical composition ($X = 0.76$, $Z = 0.0001$) and absolute luminosity ($136\,\mathrm{L}_{\odot}$). The effective temperature was used as a control parameter along the sequence. The consecutive models were computed with 1 K step at most, which was sometimes lowered to 0.1 K only. The dynamics characteristic for deterministic chaos occurs in the domain ≈ 170 K-wide, on the hot side of the domain in which modulation of pulsation was reported in **H2**. Radius variation in exemplary chaotic model is plotted in the bottom panel of Fig. 2. Fig. 3 shows the bifurcation diagram for the considered model sequence. It is a stack of grey-shaded histograms of possible values of maximum radii during pulsations, plotted versus the model's effective temperature. This diagram is very similar to bifurcation diagrams of much simpler, textbook chaotic

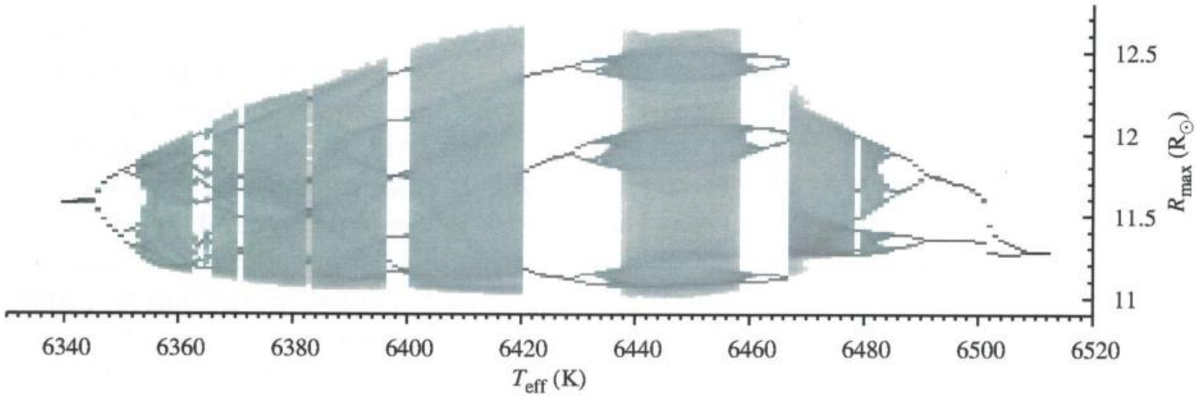

Figure 3: Bifurcation diagram for a model sequence computed in **H3**. The possible values of maximum radius are plotted as a function of the control parameter – the effective temperature.

systems, e.g. bifurcation diagram for the Lorenz system or for the iterations of the logistic map. It shows the wealth of possible dynamical effects and pulsation forms, most of which were not detected in hydrodynamic models of pulsating stars before. These phenomena are briefly characterized below.

• Period doubling cascade route to chaos. A phenomenon known also from the earlier radiative models of e.g. Kovács & Buchler (1988b). Both at the cool, and at the hot edge of the diagram presented in Fig. 3, only the simplest, single-periodic pulsation in the fundamental mode is possible (only one possible value of the maximum radius). As the control parameter is varied, we observe period doubled pulsation (two values of maximum radius), period-4 pulsation, period-8 pulsation, etc; finally chaotic band is present. The range of control parameter's values, in which the period-k pulsation is observed, decreases as k increases, as dictated by the Feigenbaum constant – a behaviour which is universal for various chaotic systems.

• The bands of deterministic chaos – grey bands in Fig. 3. Deterministic chaos does not mean random variation in the model. The model trajectories in the phase space converge to the chaotic attractor, properties of which may be studied using various techniques, e.g. the return maps.

• Windows of periodic pulsation within the chaotic band (windows of order). The characteristic feature of many chaotic systems is existence of the windows, in which periodic oscillation is observed. Instead of single-periodic pulsation, period-k pulsation is detected. There are 7 periodic windows in the computed model sequence; the largest window in Fig. 3 corresponds to period-3 pulsation.

• Type I intermittency. Evolution of the system is characterized by long phases of almost periodic behaviour interrupted with shorter bursts of chaos. The phenomenon is observed when chaos is reached through the tangent bifurcation. It is present e.g. at the cool edge of the period-3 window.

• Interior crisis and crisis induced intermittency. Crisis is a bifurcation in which the volume of the attractor changes suddenly. It is present at the hot edge of the period-3 window, where three chaotic bands (created through period doubling cascades) merge into one. Directly after the occurrence of crisis bifurcation, crisis-induced intermittency is detected. The model's trajectory is confined to the region of the former, pre-crisis attractor, with sporadic excursions out of it.

• Type-III intermittency. It is a result of subcritical period doubling bifurcation and manifests as intermittent switching between period-k and period-$2k$ pulsation.

Deterministic chaos was not detected in BL Her stars so far. It also seems that large amplitude variations due to chaos may be excluded in these stars (or such behavior is very rare). On the other hand, small amplitude chaotic variations cannot be excluded. In this context, it is important to point that light curves of classical Cepheids are nonstationary at the mmag level, which was revealed only recently thanks to precise observations of the space telescopes (np. Derekas et al., 2012; Evans et al., 2015). Observations and hydrodynamic modelling strongly indicate that deterministic chaos underlies the variability of longer period Population II Cepheids and Mira-type, and semi-regular variables. For various reasons it is difficult to compute realistic hydrodynamic models of these stars (see also below). The modelling presented in **H3** indicates, that the full spectrum of dynamical behaviours, characteristic for deterministic chaos, may be expected in these stars. Discovery of these effects requires long, regular and precise monitoring of stars' brightness, however. I look ahead to the soon expected release of the OGLE-IV photometry for Population II Cepheids, with the hope that some of these phenomena will be discovered.

In **H2** and in **H3**, only a small parts of the HR diagram, within the BL Her domain, were considered. The models were computed with the reduced eddy viscosity, which enabled the computation of very interesting dynamical behaviours with important astrophysical implications. These models cannot be regarded as representative for all Population II Cepheids, however. In fact such models are lacking. The most recent survey covering wide range of masses/luminosities/metallicities was computed with radiative code and with old opacity tables, nearly 30 years ago (Kovács & Buchler, 1988b). With the exception of a few convective BL Her-type model sequences, published by Di Criscienzo et al. (2007) a wide model survey of Population II Cepheids was not computed with the modern, convective pulsation codes. A study presented in **H5 (Smolec, 2016a)** fills this gap. In this paper, the basic set of convective parameters is exactly the same as used in **H1**, in the successful modelling of T2CEP-279. In addition a set of parameters with increased eddy viscosity was considered. The large survey consist of models of different masses and metallicities, $0.6\,\mathrm{M}_\odot$ ([Fe/H] $= -2.0, -1.5, -1.0$) and $0.8\,\mathrm{M}_\odot$ ([Fe/H] $= -1.5$), and of two just mentioned sets of convective parameters. The model grid was computed with small steps in effective temperature and in absolute luminosity, 25 K and $25\,\mathrm{L}_\odot$, respectively. Altogether several thousands of models were computed. The computed model grids are illustrated in Fig. 4.

Unfortunately, it turned out that the model survey must be limited in absolute luminosity to $600\,\mathrm{L}_\odot$ for $M = 0.6\,\mathrm{M}_\odot$, or to $1000\,\mathrm{L}_\odot$ for $M = 0.8\,\mathrm{M}_\odot$. Consequently, also the pulsation periods are limited; only close to the red edge of the instability strip, and for the highest considered luminosities, pulsation periods exceed 20 d (RV Tau domain). The above limitation is a consequence of dynamical instability detected in the luminous models. The outermost model layers tend to decouple from the model due to strong shock waves that develop in the envelope. Also in the previous radiative survey of Kovács & Buchler (1988b) model computations were limited to the above quoted luminosities. The authors only mention the difficulties with the stability of the outermost layers, which tend to decouple, without detailed analysis of the effect. In **H5** the effect is discussed

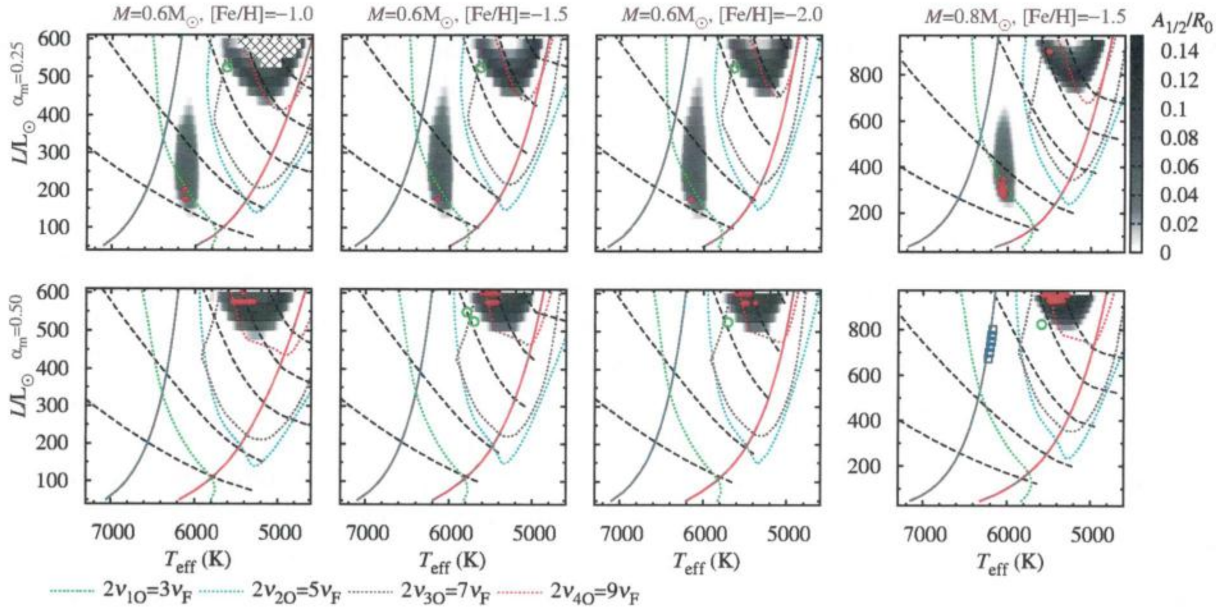

Figure 4: Possible pulsation scenarios for Population II Cepheids of different masses, metallicities and for two different sets of convective parameters ($\alpha_m = 0.25$ in the top panels and $\alpha_m = 0.5$ in the bottom panels), in the HR diagrams. The grey-shaded areas correspond to period-doubling behaviour. Models marked with filled diamonds display period-4 pulsation. Models marked with open circles show periodic modulation of pulsation. Open squares mark the models in which double-mode pulsation in the fundamental mode and in the fourth overtone was detected. Black dashed lines are lines of constant fundamental mode period, from bottom to top: 2, 4, 8, 12 and 16 d. The loci of a few half-integer resonances are marked with dotted lines, as indicated in the key in the bottom part of the figure.

in more detail for the first time. Various numerical techniques to prevent the decoupling of the outermost layer were tested – without success. The effect is likely of physical and not of numerical origin; it may correspond to pulsation enhanced mass loss in these luminous stars. Modelling of this effect is not possible without significant rewriting of the lagrangian pulsation codes; hence the limitation of the survey.

In **H5** several phenomena were studied, e.g. possible pulsation forms and their cause, non-linear period changes, changes in the radius variation curves and their possible correlation with mode resonances. The possible forms of pulsation are summarized in Fig. 4 and discussed below.

• Single-periodic pulsation in the fundamental mode; white areas in Fig. 4 (within the instability strip). The morphology of the radius variation curves clearly changes across the HR diagram, which is correlated with the two 2:1 resonances: with the second overtone (for BL Her models) and with the first overtone (for W Vir models). In the latter case, presented calculations are the first confirmation of the role of the 2:1 resonance in W Vir-type models using the non-linear modelling.

• Period-doubled pulsation; grey-shaded areas in Fig. 4. The grey-scale corresponds to the amplitude of alternations; darker the region, higher the amplitude of alternations. Two regions of period doubling are well visible in Fig. 4. The lower luminosity region extends nearly vertically at the border of the BL Her and W Vir domains. Pulsation periods are in the $2-6.5$ d range. The best model reproducing the light curve of T2CEP-279, discussed in **H1**, is located in this region. Period doubling is caused by the 3:2 resonance with the first overtone. This region ceases to exist once eddy viscosity is increased in the models (lower panel of Fig. 4). In the higher luminosity period doubling region, pulsation periods are longer, $P > 9.5$ d. This region extends within the W Vir and RV Tau domains.

• Period-4 pulsation; models marked with filled diamonds in Fig. 4. Period-4 models are located within period-doubling domains. Most likely, period doubled and period-4 models compose the first steps of the period doubling cascade which, in the models with decreased eddy viscosity, leads to chaos (paper **H3**). In the models discussed in **H5** chaos was not detected.

• Periodic modulation of pulsation; models marked with open circles in Fig. 4. This form of pulsation is possible only in the very narrow regions of the HR diagram, in the W Vir domain.

• Double-mode pulsation in the fundamental mode and in the fourth radial overtone; models marked with open squares in Fig. 4. These interesting models are found only for $M = 0.8\,\mathrm{M}_\odot$ at the blue edge of the instability strip. The fourth overtone excited in these models is a trapped mode with significant amplitude only in the external model layers. These are first models showing non-resonant double-mode pulsation involving a surface mode.

Non-linear period changes were also investigated in **H5**. Non-linear periods can be both longer, and shorter than the linear periods, by up to several per cent. The effect is not strong enough to significantly alter the period-luminosity relation for Population II Cepheids.

The above discussed model surveys indicate, that period doubling phenomenon should be common among BL Her and W Vir stars, which is clearly not the case. The effect is indeed present in some stars, but is very rare. It becomes common, only as period becomes longer than ≈ 20 d, in the RV Tau domain. The presented in-depth analysis of the hydrodynamic models shows the limitations of the currently used pulsation codes and call for improvements. The better, three-dimensional treatment of turbulent convection, which is essential process in the envelopes of these stars, seems necessary, as well as better treatment of radiation and development of non-lagrangian schemes, allowing for mass loss.

The next paper in the habilitation achievement is dedicated to RR Lyr stars, which are other group of Population II stars. This is not a modelling paper, but presents in-depth analysis of the newly discovered phenomenon: modulation of pulsation (Blazhko effect) in RRd stars – double-mode RR Lyrae stars pulsating simultaneously in the fundamental mode and in the first overtone. The phenomenon was discovered in the OGLE-IV photometry for the Galactic bulge RR Lyr stars (Soszyński et al., 2014). The effect was detected in seven stars, but no detailed analysis of the phenomenon was done. Thanks to the collaboration with the OGLE team, I had the opportunity to analyse the photometry of these interesting stars (including the most recent data) in advance. Results of the analysis are collected in **H4 (Smolec et al., 2015a)**.

For double-mode stars the period ratios are studied with the help of the Petersen diagram – Fig. 5. The majority of RRd stars form a well visible progression in this plot. For the seven modulated stars listed in Soszyński et al. (2014) the period ratios are not

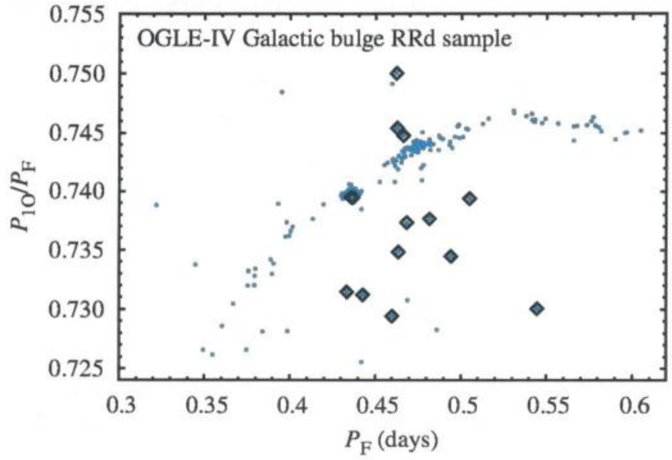

Figure 5: Petersen diagram (period ratio of the excited modes as a function of the longer period) for RRd stars of the Galactic bulge. Stars in which modulation was detected are marked with diamonds.

typical however; they are either too low or too high as compared to the majority of RRd stars of similar fundamental mode period. This motivated checking of the remaining RRd stars with not typical period ratios and led to the discovery of additional modulated stars. Altogether 15 modulated RRd stars are analysed in **H4**.

The analysis of photometric data was conducted using the software written by myself. The analysis follows a standard consecutive prewhitening technique. Significant periodicities in the data are identified with the help of the discrete Fourier transform. Variability is described with a series of sine functions with frequencies detected in the data. Amplitudes, phases and frequencies are all adjusted through non-linear least-square fitting procedure. The residual data is again inspected for the presence of additional, lower amplitude variability. In some stars a few tens of individual frequencies were identified. These are frequencies of the two radial modes, their harmonics and linear combinations. Centered on these frequencies are equidistant multiplets, a signature of periodic modulation. In some stars two or even three families of multiplets with different separations were identified; these correspond to multi-periodic modulation. The observed pulsation is non-stationary. Time variability was studied with the help of time-dependent Fourier analysis coupled with the time-dependent prewhitening (Moskalik et al., 2015). The most important properties of the modulated RRd stars are outlined below.

- Period ratio of the excited radial modes is not typical; usually it is lower than in the majority of RRd stars with similar fundamental mode period.
- Multiperiodic modulation is frequent. Two or three modulation periods are detected; typical modulation periods are in the 20 – 300 d range; modulation amplitude vary from a few per cent to hundred per cent of the radial mode amplitudes.
- In some stars the two radial modes are simultaneously modulated with a common period. More commonly however, modulation dominant for the fundamental mode has different period than modulation dominant for the first overtone. Modulation of only one radial mode is also possible.
- Amplitudes and frequencies of the radial modes irregularly vary on a time-scale of a few hundred to a thousand days; The observed modulations are also irregular.

When **H4** was submitted to the journal, a paper by Jurcsik et al. (2014) was published, in which the authors report the discovery of four modulated RRd stars in the globular cluster M3. Properties of these stars are very similar to the properties of variables observed in the Galactic bulge.

Just as in the case of the Blazhko effect in the single-periodic RR Lyrae stars, the cause of the modulation in the RRd stars remains unknown. In one of the modulated RRd stars a mode switching event was observed. Single-periodic RRab star switched into double-mode (RRd) pulsation (Soszyński et al., 2014). The fundamental mode was modulated before and after the mode switching event. In **H4** it is suggested that these two phenomena: modulation in RRd stars and mode switching, might be connected. Verification of such hypothesis on observational grounds is very difficult however. Mode switching is extremely rare phenomenon; to capture such event, regular monitoring of variables over tens of years is necessary. The observed, not typical period ratios in the modulated stars, represent no difficulty for the stellar pulsation theory (see Smolec, 2016b); the lower ones are reproduced assuming higher metallicity in the models. High-metallicity RR Lyr stars are not rare in the Galactic bulge. However, the periods of the modulated RRd stars are longer than periods of the high-metallicity non-modulated stars, which are located in the short-period tail of the main progression of RRd stars visible in Fig. 5 (Soszyński et al., 2011a).

The last paper in the habilitation achievement is dedicated to classical Cepheids and to other dynamical effect: double-mode pulsation. In **Smolec & Śniegowska (2016)**, **H6**, the OGLE observations for a selection of first overtone Cepheids from the Small Magellanic Cloud (SMC) are analysed. In these stars additional, low-amplitude variability, with period shorter than first overtone period, is detected. The period ratios fall in the $P_{\rm x}/P_{\rm 1O} \in (0.60, 0.65)$ range. First stars of this type were discovered in the Large Magellanic Cloud (Soszyński et al., 2008; Moskalik & Kołaczkowski, 2009), but the largest sample – 138 stars – was detected in the SMC (Soszyński et al., 2010). In Soszyński et al. (2010) no detailed analysis for these stars was done. The only information given, is the period of the additional variability, which can be found in the remarks file in the OGLE ftp archive[4]. Photometric data for these stars are analysed in **H6**. In the Petersen diagram the stars form three sequences, as illustrated in Fig. 6. The additional periodicity cannot be interpreted as due to radial mode (Dziembowski & Smolec, 2009).

A similar form of pulsation is detected in RR Lyr stars pulsating in the radial first overtone mode (RRc or RRd stars). The period ratio of the detected two periodicities falls into a similar range, typically it is around 0.61. The properties of RR Lyr stars that display this form of pulsation are well known, also thanks to studies in which I participated (eg. Moskalik et al., 2015; Netzel, Smolec & Moskalik, 2015b). In frequency spectra of these stars, subharmonics of the additional variability, i.e. signals at $\nu_{\rm sh} = 1/2\nu_{\rm x}$ ($\nu_{\rm x} = 1/P_{\rm x}$), are often detected. This is a very important feature of these stars. In the new model proposed to explain the nature of this variability, proposed by Dziembowski (2016), the signal at subharmonic frequency is interpreted as due to non-radial mode of degree in the $\ell = 7 - 9$ range (these are the so-called strongly trapped unstable modes). The variability detected at $\nu_{\rm x}$, which is typically of higher amplitude, corresponds to the harmonic frequency $\nu_{\rm x} = 2\nu_{\ell}$. Because of geometric cancellation, it is difficult to

[4]ftp://astrouw.edu.pl/ogle3/OIII-CVS/smc/cep/remarks.txt

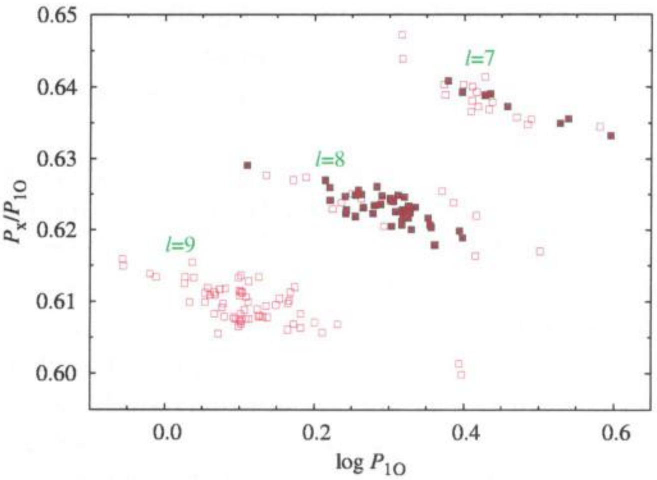

Figure 6: Petersen diagram for first overtone Cepheids from the Small Magellanic Cloud, with additional periodicity detected. Filled symbols correspond to stars in which subharmonics of the additional variability were detected. At each sequence, the corresponding mode degree from the Dziembowski's model is given.

detect non-radial modes of relatively high degree. Their observed amplitudes depend on ℓ. On the other hand, due to non-linear and geometric effects, the mode harmonic, i.e. variability with frequency $2\nu_\ell$, can gain significant amplitude.

In **H6** the first in-depth analysis of pulsation of first overtone Cepheids with additional periodicity is presented. The analysis followed a standard scheme, just as described above for **H4**. The analysis was conducted using the same software written by myself. The most important result is the detection of subharmonics in 35 per cent of the analysed stars. Subharmonics were not detected in any previous study of these stars. Most importantly, stars in which subharmonics are detected, are not randomly distributed in the Petersen diagram, as illustrated in Fig. 6. In this plot, the filled symbols correspond to stars in which subharmonics were detected. They were detected in 74 per cent of stars forming the middle sequence and in 31 per cent of stars forming the top sequence. Subharmonics were not detected in stars of the bottom sequence. The described distribution well agrees with the Dziembowski (2016) model, in which subharmonics are due to non-radial modes of $\ell = 7$ (top sequence), $\ell = 8$ (middle sequence) and $\ell = 9$ (bottom sequence). The geometric cancellation is lower for even-ℓ modes. It is lower for $\ell = 8$ than for $\ell = 7$ or $\ell = 9$. In addition, the geometric cancellation is lower for $\ell = 7$ than for $\ell = 9$. Consequently, the probability of detecting subharmonics is the highest for the middle sequence. Then, subharmonics should be detected more easily for stars of the top sequence than for stars of the bottom sequence, for which the expected, observed amplitude of the non-radial mode is the lowest. For the analysed OGLE data it is below the detection limit, as no subharmonics were detected.

In **H6** properties of the classical Cepheids with non-radial mode excited were studied in detail. Other important features of these stars are the following.

• Amplitude of the additional variability is low; typically between 2 and 4 per cent of the radial first overtone amplitude (2 – 5mmag).

• In the frequency spectrum signals detected at ν_x and at $1/2\nu_x$ are non-stationary.

The detected structures are broad and complex. The structures detected at subharmonic frequency are typically broader than structures detected at ν_x. It is in qualitative agreement with the Dziembowski's model.

• Properties of the radial first overtone mode in stars with additional periodicity are the same as in single-periodic first overtone Cepheids.

• The properties of the analysed Cepheids are qualitatively the same as properties of the RRc stars with additional variability. Hence, the nature of the discussed form of pulsation must be the same in the two groups of classical pulsators.

In **H6** the possible influence of the observational selection effects on the obtained results was carefully checked and discussed.

Short summary

In the series of four papers, **H1**, **H2**, **H3** and **H5**, a comprehensive modelling of Population II Cepheids with up-to-date, convective pulsation code (one of the three similar codes used nowadays) was presented. Similar calculations published in the past were done with radiative codes and for strongly limited number of model sequences. The series started with the modelling of a single star – first BL Her star showing period doubling alternations, as predicted 20 years earlier based on hydrodynamic modelling (Buchler & Moskalik, 1992). The next three papers present in-depth analysis of interesting dynamical phenomena found in the models of Population II Cepheids; majority of these phenomena were not detected in the observations, yet. With the growing flow of top-quality data from ground-based sky surveys and from space telescopes, one may hope that the discovery of new dynamical effects in the pulsation of Population II Cepheids is just a matter of time. The best example is the discovery of the Blazhko modulation in 15 double-mode RR Lyrae stars in the OGLE-IV data (Soszyński et al., 2014, and **H4**). The in-depth analysis of this phenomenon was presented in **H4**. At the fall of 2016 the release of OGLE-IV data for Population II Cepheids from the Galactic bulge (and next from the Magellanic Clouds) is expected. Analysis of these data in search for the new dynamical phenomena is among my most important scientific plans for the near future. In the last paper in the habilitation achievement, **H6**, detailed analysis of other dynamical effect, beat pulsation in the radial and non-radial modes, is presented. The in-depth analysis of first overtone Cepheids from the SMC, showing this form of pulsation, strongly supports the new model propsed by Dziembowski (2016), in which the excited non-radial modes and their excitation mechanism are identified.

5. Presentation of the remaining scientific achievements.

Short description of other projects.

Since 2010 I have been participating in the analysis of photometric data gathered with the *Kepler* space telescope (now *K2* mission), within the *Kepler Asteroseismic Science Consortium* (KASC). I co-author nine refereed papers which resulted from KASC collaboration. My most significant contributions concern the analysis of modulated RR Lyr stars. In Kolenberg et al. (2011) I analysed the *Kepler* observations, in particular the light curve changes over the Blazhko cycle, in RR Lyr – the eponym of the class. In Guggenberger et al. (2012), with the help of pulsation models, I discussed the possible interpretations for additional periodicities detected in V445 Lyr. In a study of non-modulated RR Lyr stars by Nemec et al. (2011), I computed a series of non-linear pulsation models that supported the interpretation of observations. The *Kepler* RR Lyr observations were used in Smolec et al. (2011). In this study, with the help of hydrodynamic pulsation models and their comparison with observations, we have indicated weak points of the Stothers (2006) model proposed to explain the Blazhko modulation.

I am a member of the *Araucaria* project, in which I take part in the analysis of evolution and pulsation of giant stars – members of the eclipsing binary systems. My largest contribution so far concerns the pulsation modelling of variable of new type, OGLE-BLG-RRLYR-02792, which mimics RR Lyr pulsation, but with significantly lower mass (the so-called binary evolution pulsator; Pietrzyński et al., 2012). In Smolec et al. (2013) a successful modelling of RRLYR-02792 light and radial velocity curves was presented. A model survey for the expected new class of variable stars was conducted and light/radial velocity curves' features, that might be helpful in distinguishing these stars from classical RR Lyr pulsators, were identified. With the help of publicly available stellar evolution code MESA (Paxton et al., 2015), I model the evolution of the eclipsing binary systems. In Suchomska et al. (2015), I computed a grid of stellar evolution models for ASAS J180057-2333.8 and analysed the effects of overshooting.

Analysis and interpretation of photometry for classical pulsators observed by the OGLE project is one of the main goals of my research. In a series of papers led by Henryka Netzel, a Warsaw University student whom I supervise, we have analysed the first overtone RR Lyr stars observed towards the Galactic bulge. In Netzel, Smolec & Dziembowski (2015) we report the discovery of a new class of double-periodic pulsators, with the dominant radial first overtone, and additional, low-amplitude, long-period variability. Period of the additional variability is even longer than the fundamental mode period. It is a new and very puzzling form of RR Lyr pulsation, for which explanation is missing. In Netzel, Smolec & Moskalik (2015a,b) we search for and analyse the properties of other double-periodic pulsators, with dominant radial first overtone and additional, shorter period variability, with the characteristic period ratios of the excited modes in the $P/P_{1O} \in (0.60, 0.64)$ range. The number of stars, members of this class, was increased by a factor of ten, which allowed us to make detailed analysis of properties of this group. A very similar form of pulsation is present in first overtone Cepheids and was studied in **H6**. These analyses clearly point that in RR Lyr stars and in Cepheids the nature of the additional variability, and consequently the underlying excitation mechanism, must be the same. Our results support the model proposed recently by Dziembowski (2016), in which the additional variability is due to excitation of strongly trapped non-radial modes.

Another paper, in which OGLE data are analysed is Smolec et al. (2015b), in which a discovery of very peculiar triple-mode RR Lyr-type variable with period doubling is reported.

As mentioned above, I actively collaborate with Master's students. Each year I propose research projects for the summer student programme at Nicolaus Copernicus Astronomical Center. So far I supervised four students. The most notable results of the summer programme are three refereed papers with Henryka Netzel. Collaboration with Henryka Netzel lasts for more than two years. In February she applied for the *Diamond Grant* – a programme of the Polish Ministry of Science and Higher Education intended to support the PhD studies; I act as her scientific mentor in the application. The cooperation with Marzena Śniegowska (co-author of **H6**) also continues; she now works on a research project (analysis of OGLE data for LMC Cepheids) under my supervision.

The in-depth analysis of observations done in **H4**, **H6**, or e.g. in Netzel, Smolec & Moskalik (2015b) or Smolec et al. (2015b), was possible thanks to dedicated software for time-series analysis written by myself. The source code of this software counts nearly 15000 lines. It runs in a terminal (similar to e.g. IRAF software) and offers the user more than 90 commands. It implements more advanced techniques like time-dependent Fourier analysis and time-dependent prewhitening. It can run in the batch mode and be used for automatic analysis of large data sets. The results are displayed in the graphic mode and their interactive analysis is possible. In the future, the code will be made public.

Altogether, I co-author 34 refereed publications (28 published after obtaining PhD degree). I am the first author in 14 of them (10 published after PhD). I also co-author 28 conference contributions (19 as first author). Total number of citations for all papers is 801, my h-index is 16 (NASA/ADS, 30 March 2016).

I have presented my results at numerous scientific conferences in Poland and abroad. I gave 6 invited talks, 11 contributed talks and 12 poster presentations. I was among the members of the Scientific Organizing Committe of the *RRL2015: High-precision studies RR Lyrae Stars* conference, which took part in October 2015 in Visegrad, Hungary. I proposed to make a conference focused on RR Lyr stars a cyclic event and declared to organize its next edition in Poland, in 2017.

I received a few research grants. In 2012 I was awarded the Iuventus+ grant from the Polish Ministry of Science and Higher Education (IP2012 036572, project title *Period doubling and chaos in hydrodynamic type-II Cepheid models*, dates 06.2013-11.2015, funding received 114 540PLN). I am also the principal investigator for two National Science Center OPUS grants awarded in 2012 (2012/05/B/ ST9/03932, project title *Multi-mode, nonradial and modulated pulsation of RR Lyrae stars and Cepheids*, dates 01.2013-08.2016, funding received 419 600PLN) and in 2015 (2015/17/B/ST9/03421, project title *Classical pulsators through diverse stellar systems: contrast between pulsation modes*, dates 02.2016-02.2019, funding received 419 580PLN). I am co-PI (with Dr Katrien Kolenberg) of the joint research project for years 2016–2018, *Probing cosmic standard candles in the space age* (collaboration between Polish Academy of Sciences and Research Fund – Flanders). I am also co-investigator in a few National Science Center grants supporting the *Araucaria* team (PI prof. Grzegorz Pietrzyński).

In 2015 I was awarded the prestigious three-year scholarship from the Polish Minster of Science and Higher Education for the outstanding young researchers.

I am a member of the Polish Astronomical Society (since 2013) and of the International

Astronomical Union (since 2012; Division G, Commissions G1 *Binary and Multiple Star Systems*, G3 *Stellar Evolution* and G4 *Pulsating Stars*). Since 2016 I am one of the 12 voting members of the *BRITE Executive Science Team (BEST)*. BEST acts as the steering committee for the constellation of 5 BRITE nano-satellites including two Polish, Lem and Heweliusz. I am a member of the *Kepler Asteroseismic Science Consortium*, of the Cepheid and RR Lyrae working group. We analyse the data gathered by space telescope *Kepler* (now *K2 mission*). I am the PI of one and co-I of a few *K2* observing proposals submitted in the framework of the *Kepler Guest Observer Program*. I am also a member of the *Araucaria* project; its main goal is the improvement and precise calibration of the cosmic distance scale.

I regularly peer review for *Monthly Notices of the Royal Astronomical Society* and *Astrophysical Journal*. I also peer reviewed for *Astronomy & Astrophysics*, *Astronomical Journal*, *Publications of the Astronomical Society of the Pacific (PASP)* and *Acta Astronomica*.

References

Bono G., Stellingwerf R.F., 1994, ApJ Suppl. Ser., 93, 233
Buchler J.R., Kolláth Z., 2011, ApJ, 731, L24
Buchler J.R., Moskalik P., 1992, ApJ, 391, 736
Buchler J.R., Kolláth Z., Serre T., 1996, ApJ, 462, 489
Christy, R.F., 1966, ApJ, 144, 108
Cox, J.P., Theory of stellar pulsation, Princeton University Press
Derekas A., et al. (with Smolec, R.), 2012, MNRAS, 425, 1312
Di Criscienzo M., Caputo F., Marconi M., Cassissi S., 2007, A&A, 471, 893
Dziembowski W., 2016, Comm. Konkoly Obs., vol. 105, in press, arXiv:1512.03708
Dziembowski W., Smolec R., 2009, AIP Conf. Proc., 1170, 83
Evans N.R., et al., 2015, MNRAS, 446, 4008
Guggenberger E., et al. (with Smolec, R.), 2012, MNRAS, 424, 649
Iglesias C.A., Rogers F.J., 1991, ApJ, 371, L73
Jurcsik J., et al., 2014, ApJ 797, L3
Kolenberg K., et al., 2010, ApJ, 713, L198
Kolenberg K., et al. (with Smolec, R.), 2011, MNRAS, 411, 878
Kolláth Z., Molnár L., Szabó R., 2011, MNRAS, 414, 1111
Kolláth Z., Buchler J.R., Serre T., Mattei J., 1998, A&A, 329, 147
Kolláth Z., et al., 2002, A&A, 385, 2002
Kuhfuß R., 1986, A&A, 160, 116
Kovács G., Buchler J.R., 1988a, ApJ, 324, 1026
Kovács G., Buchler J.R., 1988b, ApJ, 334, 971
Moskalik P., Buchler J.R., 1990, ApJ, 355, 590
Moskalik P., Kołaczkowski Z., 2009, MNRAS, 394, 1649
Moskalik P., Smolec, R., Kolenberg, K., et al., 2015, MNRAS, 447, 2348
Nemec, J.M., Smolec R., Benkő J.M., et al., 2011, MNRAS, 417, 1022
Netzel H., Smolec R., Moskalik P., 2015a, MNRAS, 447, 1173
Netzel H., Smolec R., Moskalik P., 2015b, MNRAS, 453, 2022

Netzel H., Smolec R., Dziembowski W., 2015, MNRAS Lett., 451, L25
Paxton B., et al., ApJ Suppl. Ser., 220, 15
Pietrinferni A., Cassisi S., Salaris M., Castelli F., 2006, ApJ, 642, 797
Pietrzyński G., et al., 2012, Nature, 484, 75
Smolec R., 2005, Acta Astron., 55, 59
Smolec R., 2015, EPJ Web of Conferences, 101, 06059
Smolec R., 2016a, MNRAS, 456, 3475, (**H5**)
Smolec R., 2016b, Comm. Konkoly Obs., 105, in press, arXiv:1512.08420
Smolec R., Moskalik P., 2008a, Acta Astron., 58, 193
Smolec R., Moskalik P., 2008b, Acta Astron., 58, 233
Smolec R., Moskalik P., 2012, MNRAS, 426, 108, (**H2**)
Smolec R., Moskalik P., 2014, MNRAS, 441, 101, (**H3**)
Smolec R., Śniegowska M., 2016, MNRAS, 458, 3561, (**H6**)
Smolec R., Moskalik P., Kolenberg, K., et al., 2011, MNRAS, 414, 2950
Smolec R., Soszyński I., Moskalik P., et al., 2012, MNRAS, 419, 2407, (**H1**)
Smolec R., Pietrzyński G., Graczyk D., et al., 2013, MNRAS, 428, 3034
Smolec R., Soszyński I., Udalski A., et al., 2015a, MNRAS, 447, 3756, (**H4**)
Smolec R., Soszyński I., Udalski A., et al., 2015b, MNRAS, 447, 3873
Suchomska K., Graczyk D., Smolec R., et al., 2015, MNRAS, 451, 5170
Soszyński I., et al., 2008, Acta Astron., 58, 163
Soszyński I., et al., 2010, Acta Astron., 60, 17
Soszyński I., et al., 2011a, Acta Astron., 61, 1
Soszyński I., et al., 2011b, Acta Astron., 61, 285
Soszyński I., et al., 2014, Acta Astron., 64, 177
Stellingwerf R.F., 1975, ApJ, 195, 441
Stellingwerf R.F., 1982, ApJ, 262, 330
Stothers R.B., 2006, ApJ, 652, 643
Udalski A., Szymański M.K., Szymański G., 2015, Acta Astron., 65, 1

Warszawa, 5.04.2016 Radosław Smolec

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