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Selected new results on pulsating variable stars

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Abstract. Recent progress in the studies of pulsating variable stars is summarized from an observational point of view. A number of unexpected phenomena have been revealed in the case of pulsators in the classical instability strip. These discoveries – lacking theoretical explanation yet – make pulsating stars more valuable objects for astrophysics than before. The emphasis is laid on Cepheids of all kind and RR Lyrae type variables, as well as binarity among pulsating variable stars.

Key words: pulsating variables – radial pulsation – nonradial pulsation – binarity

1. Introduction

This paper is intended to be an update and continuation of the review published in the proceedings of the previous conference held in Tatranská Lomnica on similar topic five years ago (Szabados, 2014). The reader will find repetitions only in unavoidable cases.

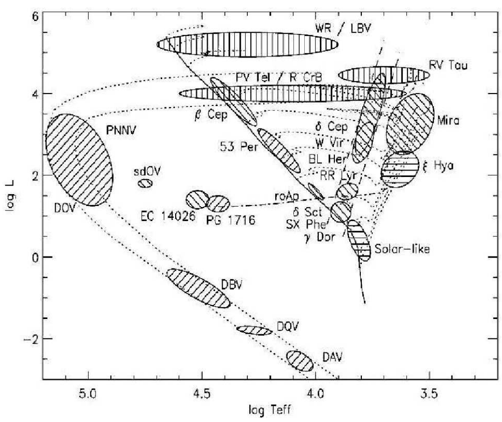

Figure 1. The H-R diagram showing the location of various types of pulsating variables (Jeffery, 2008). Some more types are listed in Table 1.

Table 1. Classification of pulsating variable stars.

Type	Design.	Spectrum	Period	Amplitude in V band (m)	Remark*
Cepheids	DCEP	F-G Iab-II	1-135 d	0.03-2	
	DCEPS	F5-F8 Iab-II	<7 d	<0.5	1OT
	CEP(B)	F5-F6 Iab-II	2-7 d	0.1-1	beat Cepheids
BL Boo	ACEP	A-F	0.4-2 d	0.4-1.0	anomalous Cepheids
W Vir	CWA	FIb	>8 d	0.3-1.2	
BL Her	CWB	FII	<8 d	<1.2	
RV Tau	RV, RVA	F-G	30-150 d	up to 3	
	RVB	F-G	30-150 d	up to 3	var. mean brightness
RR Lyr	RRAB	A-F giant	0.3-1.2 d	0.4-2	
	RRC	A-F giant	0.2-0.5 d	<0.8	1OT
	RR(B)	A-F giant	0.2-1.0 d	0.4-2	double-mode puls.
δ Sct	DSCT	A0-F5 III-V	0.01-0.2 d	0.003-0.9	R+NR
SX Phe	SXPHE	A2-F5 subdw.	0.04-0.08 d	<0.7	Pop. II
γ Dor	GDOR	A7-F7 IV-V	0.3-3 d	<0.1	NR, low degree g-mode
roAp	ROAP	B8-F0 Vp	5-20 min	0.01	NR p-modes
λ Boo	LBOO	A-F	<0.1 d	<0.05	Pop. I, metal-poor
Maia		A			to be confirmed
V361 Hya	RPHS, EC14026	sdB	80-600 s	0.02-0.05	NR, p-mode
V1093 Her	PG1716, Betsy	sdB	45-180 min	<0.02	g-mode
DW Lyn		subdwarf		<0.05	V1093 Her + V361 Hya
GW Vir	DOV, PG1159	HeII, CIV	300-5000 s	<0.2	NR g-modes
ZZ Cet	DAV	DAV	30-1500 s	0.001-0.2	NR g-modes
DQV	DQV	white dwarf	7-18 min	<0.05	hot carbon atmosphere
V777 Her	DBV	He lines	100-1000 s	<0.2	NR g-modes
Solar-like oscill.		F5-K1 III-V	<hours	<0.05	many modes
Mira	M	M, C, S IIIe	80-1000 d	2.5-11	small bolometric ampl.
Small ampl. red var.	SARV	K-M IIIe	10-2000 d	<1.0	
Semi-regular	SR	late type I-III	20-2300 d	0.04-2	
	SRA	M, C, S III	35-1200 d	<2.5	R overtone
	SRB	M, C, S III	20-2300 d	<2	weak periodicity
	SRC	M, C, S I-II	30-2000 d	1	
	SRD	F-K I-III	30-1100 d	0.1-4	
	SRS	late type	5-30 d	0.1-0.6	high-overtone puls.
Long-period irregular	L	late type			slow
	LB	K-M, C, S III			
	LC	K-M I-III			
Protoplan. nebulae	PPN	F-G I	35-200 d		SG, IR excess

* R = radial; NR = non-radial; 1OT = first overtone; SG = supergiant. Spectrum is given for maximum brightness for large amplitude variables.

Table 1. Classification of pulsating variable stars (continued).

Type	Design.	Spectrum	Period	Amplitude in V band (m)	Remark*
53 Per		O9-B5	1-3 d		NR
β Cep	BCEP	O8-B6 I-V	0.1-0.6	0.01-0.3	R + NR
	BCEPS	B2-B3 IV-V	0.02-0.04	0.015-0.025	R + NR
SPB	SPB	B2-B9 V	0.4-5 d	<0.5	high radial order, low degree g-modes
Be	BE, LERI	Be	0.3-3 d		NR (or rotational?)
LBV	LBV	hot SG	30-50 d		NR?
α Cyg	ACYG	Bep-Aep Ia	1-50 d	~0.1	NR, multiperiodic
BX Cir		B	0.1 d	~0.1	H-deficient
PV Tel	PVTELI	B-A Ip	5-30 d	~0.1	He SG, R strange mode
	PVTELII	O-B I	0.5-5 d		H-def. SG, NR g-mode
	PVTELIII	F-G I	20-100 d		H-def. SG, R?
Fast Rotating Puls. B Stars	FaRPB	B	<55 d	0.001-0.004	fast rotators
Blue Large Ampl. Puls.	BLAP	O-B	20-40 min	0.2-0.4	
Binary Evolution Pulsators	BEP				RR Lyr 'impostors'
Heartbeat Variables					binary stars on eccentric orbit

Oscillations are ubiquitous in stars. Hot and cool stars, luminous and low luminosity stars can also pulsate, as is seen in the Hertzsprung-Russell (H-R) diagram showing the location of different types of pulsating variable stars (Fig. 1). Even our Sun is a pulsating variable star in which millions of non-radial oscillation modes have been excited.

Table 1 is an up-to-date overview of different types of pulsating variables whose oscillations are excited by various mechanisms. In the last years, four new types of pulsating variables – listed in the end of Table 1 – were discovered:
- fast rotating pulsating variables,
- blue large amplitude pulsators,
- binary evolution pulsators,
- heartbeat variables.

The first representatives of fast rotating pulsating stars were discovered by Degroote et al. (2009) and Mowlavi et al. (2013). Stars belonging to this new variability type also obey a period-luminosity (P-L) relationship, but its cause differs from that of the P-L relationship for classical pulsating variables (Mowlavi et al., 2016).

Blue large amplitude pulsators vary with a short period, like δ Scuti stars, but with a larger amplitude and their effective temperature is about 30 000 K (Pietrukowicz et al., 2017). Their luminosity corresponds to stars fainter than those of main sequence stars of similar temperature. Such objects can be formed after merging of two low mass stars.

Binary evolution pulsators resemble RR Lyrae type variables phenomenologically (this is why their nickname is RR Lyrae impostors), but their mass is lower (about half) than that of the RR Lyraes on the horizontal branch of the H-R diagram. Such stars can occur in the instability strip of classical pulsators as a result of mass transfer in a binary system (Pietrzyński et al., 2012). Binary evolution pulsators can mimic Cepheid type behaviour, too. Based on a population synthesis calculation, Karczmarek et al. (2017) concluded that about 0.8% of seemingly RR Lyrae type variables are, in fact, binary evolution pulsators, while the contamination of Cepheids by such impostors is higher, about 5%.

The heartbeat variables are composed of two stars on an eccentric orbit and tidal interaction excites a low amplitude pulsation in at least one of their components. The first such binary star was found in the Kepler field (Welsh et al., 2011), and soon after this discovery, a number of such systems have been identified (Thompson et al., 2012).

Pulsating variable stars are important objects for astrophysics, cosmology, and studies of galactic structure, as well. From the point of view of astrophysics, stellar oscillations provide us with information on internal structure of the stars and their evolutionary phase. The cosmological use of pulsating variable stars is based on the fact that several types of luminous pulsators obey a specific P-L relationship which is indispensable in extragalactic distance determination. The galactic structure can be traced by studying spatial distribution of various types of pulsating stars of different ages/populations within a galactic system.

Importance of pulsating stars is supported by the frequency of occurrence of such variables, as well. About 40% of the designated variable stars in the General Catalogue of Variable Stars (GCVS, Samus et al., 2017) are pulsating variables. Because of the strict criteria, GCVS designation has been assigned to only less than 60 000 variable stars, meanwhile the number of known variables is over half a million. The Variable Star Index (VSX) maintained at the AAVSO website contains 543 564 stars in October 2018, while data on 550737 variable stars have been published in the Gaia Data Release 2 in April 2018, including more than 100 000 RR Lyrae type variables and 10 000 Cepheids (Gaia Collaboration, Brown et al., 2018). Keeping in mind the fact that about 10% of the targets of the Hipparcos astrometric satellite were found to be variable in brightness, the expected number of variable stars exceeds a hundred million among the more than one billion targets of the ESA's Gaia project. Naturally, the number of pulsating stars is also extremely large among the Gaia sample of stars brighter than $20\overset{\mathrm{m}}{.}7$ magnitude.

When observing pulsating stars, temporal coverage (duration of the time series) is a critical aspect for studying multiperiodicity, changes in frequency content, modal amplitudes, etc. Therefore, time consuming photometry of pulsating variables is a realm of small telescopes. If the astroclimate of the observing site does not allow high-precision photometry, observations of variable stars with a large photometric amplitude are recommended.

A tutorial on the basic notions related to stellar pulsation is available in the pdf version of the author's presentation delivered during the conference (Szabados, 2018).

2. Importance of binarity among pulsating variables

It is a remarkable fact that binarity is important in at least three of the four recently defined types of pulsators mentioned above. In addition, pulsating stars in eclipsing binary systems are invaluable sources of information because such pairs of stars offer a unique possibility for an accurate determination of the mass, radius and luminosity of the components and test predictions of the pulsation theory (see e.g. Pilecki, 2018). Moreover, bright companions can falsify the calibration of the P-L relationship without correcting for their additional light. Therefore an important task is to reveal binary systems among pulsating stars used for standard candles.

A useful hint for binarity is the appearance of the light travel time effect in the $O - C$ diagram due to the orbital motion in a binary system. However, seemingly periodic variations in the pulsation period are insufficient for declaring that the given pulsator is a member in a binary system if the light-time effect solution results in unrealistic stellar parameters, or orbital elements as testified by the case of the RR Lyrae variable Z CVn (Skarka et al., 2018).

A close companion can even trigger stellar oscillations in the other star of the binary system. This happens in the case of heartbeat variables. Another kind of externally triggered pulsation was observed in the symbiotic nova RR Tel preceding its eruption in 1948 (Robinson, 1975).

Now it is clear that long-period variations in the mean brightness of RV Tauri stars (RVB subtype) are also caused by the binarity of these pulsators (Kiss & Bódi, 2017, and references therein).

3. Rapid evolutionary episodes in pulsating variables

In this section, recently observed interesting examples of rapid evolutionary episodes are mentioned continuing the list published in Szabados (2014).

The Type II Cepheid, V725 Sgr, experienced a sudden transition to a red semi-regular variable: its pulsation period increased from about 10 days to 90 days within a century (Percy et al., 2006).

The OGLE photometric survey is a treasure-house for finding peculiar behaviour among various pulsators. For example, Soszyński et al. (2014) revealed three RR Lyrae type variables which experienced mode switching from a double-mode pulsation to a simple fundamental mode oscillation, or vice versa. Their sample consisted of about 38 000 RR Lyrae stars in the Galactic Bulge, so such rapid transitions are not extremely rare. Similarly, the OGLE project resulted in the discovery of a Cepheid variable, OGLE-SMC-CEP-3043, that stopped its pulsations within 15 years of observation (Soszyński et al., 2015b).

Delta Scuti stars perform both radial and non-radial pulsations and many modes can be excited simultaneously. It is noteworthy that temporal variations occur in both the observed frequencies and the modal amplitudes on a time scale of months to years. A thoroughly studied example is the case of AI CVn (Breger et al., 2017; Breger & Lenz, 2018).

4. New results on classical Cepheids

Cepheids have been considered as extremely stable pulsators for long. Studies based on very accurate photometric data collected by space telescopes, however, revealed that this paradigm has to be revised. Cycle-to-cycle changes occur in the pulsation period and light curve shape of V1154 Cygni (Derekas et al., 2012). In spite of this slight period flickering, the average pulsation period has remained stable on the time scale of decades. From the analysis of Kepler data covering four years Derekas et al. (2017) pointed out that the light curve of V1154 Cyg is modulated. This effect resembles the Blazhko effect commonly appearing among RR Lyrae stars. In the case of V1154 Cyg, the cycle length of the modulation is about 159 days.

The Blazhko effect was revealed in other classical Cepheids, too. Berdnikov et al. (2017) found a strong Blazhko modulation in the light curve of ASAS 160125-51503 with a cycle length of 1242 days. The pulsation of the best known Blazhko Cepheid, V473 Lyrae (Molnár et al., 2013) is subjected to period doubling, as revealed from uninterrupted photometry obtained with the MOST space telescope (Molnár et al., 2017). Such period doubling was recently observed in Blazhko RR Lyrae stars, too.

A part of fundamental-mode Cepheids in both Magellanic Clouds have periodically modulated light curve (Smolec, 2017). Though the amplitude of the modulation is tiny, the phenomenon is intriguing.

In addition to the slightly unstable light curve, the radial velocity phase curve of classical Cepheids is also non-repetitive because variations in the atmospheric velocity gradient result in radial velocity changes (Anderson, 2016).

Most of Cepheids are single-mode pulsators, but a simultaneously excited double-mode oscillation also exists among this type of variable stars and even Cepheids pulsating simultaneously in three radial modes have been identified (Moskalik, 2013). A long-term modulation of the light curve has been observed among the double-mode Cepheids of the Magellanic Clouds (Moskalik & Kołaczkowski, 2009). A characteristic feature of this modulation is that the amplitudes of modes involved vary in an anticorrelated manner.

The period ratio of the firts overtone and the fundamental mode pulsation is sensitive to the atmospheric iron abundance of double-mode Cepheids (Sziládi et al., 2007). Recently, Sziládi et al. (2018) published formulae allowing calculation of iron abundance of double-mode Cepheids from the Fourier decomposition of the light curve.

The OGLE data show that additional periodic variability exists among first overtone Cepheids in the Magellanic Clouds with a photometric amplitude of 2-5 millimagnitude. The period is in the range of 0.60-0.65 of the value of the main pulsation period (Smolec & Śniegowska, 2016). In the Petersen diagram, three well separated sequences are outlined corresponding to stars that pulsate with this additional periodicity (see left panel of Fig. 2). From the period ratio, the slightly excited oscillation cannot be any radial mode. Pulsation with a similar period ratio has been observed in first overtone RR Lyrae variables. According to Dziembowski's (2016) theoretical calculations, the three new sequences in the Petersen diagram correspond to stars pulsating in non-radial modes of angular degrees 7, 8, and 9.

Anomalous Cepheids are probably old coalesced binaries crossing the instability strip (Soszyński et al., 2015a). Thus they are examples for binary evolution pulsators. Because anomalous Cepheids have separate P-L relationships, their individual representatives can be readily identified in the Magellanic Clouds based on the apparent mean brightness, unlike their Galactic counterparts.

5. New results on Type II Cepheids

Type II Cepheids are low-mass, usually metal-poor pulsators oscillating in the radial fundamental mode. Their pulsation is less stable compared with the oscillation of classical Cepheids. Noticeable light-curve changes occur from one cycle to the other, and the pulsation period can vary rapidly. In addition to these long known interesting facts, other peculiarities have been revealed quite recently (Smolec et al. 2018). The following dynamical phenomena have been identified in Type II Cepheids of the OGLE collections:
- double-mode pulsation in the short period (BL Her) subgroup;
- period doubling behaviour in the BL Her type variables;
- quasi-periodic light-curve modulation in all three (BL Her, W Vir, and RV Tau) subgroups of Type II Cepheids.
- Moreover, period doubling was revealed in Galactic W Vir stars (Plachy, 2018).

DF Cyg turned out to be the first RVb type variable star showing low-dimensional chaos in its pulsation (Plachy et al., 2018). This is only the third known case of chaotically pulsating RV Tauri stars, the other two variables belong to the RVa subgroup.

6. New results on RR Lyrae type variables

In addition to their periodic pulsation, the old RR Lyr type variables situated on the horizontal branch of the H-R diagram also show various other effects worthy of studying in detail. At the turn of the millennium, RR Lyrae variables were thought to be monoperiodic radial pulsators part of which shows a modulated light curve. Now we know that RR Lyrae stars are multiperiodic with radial and nonradial modes excited. The long known, though still mysterious, phenomenon is the Blazhko effect, a slow, cyclic (not periodic) modulation of the light curve amplitude and phase appearing simultaneously is present in about 50% of these variable stars. It is typical that more than one modulation cycle is present in a given star. A gallery of the Blazhko modulation is published by Benkő et al. (2014). It is promising that new models involving interactions between radial and nonradial modes of oscillation, as well as coupling between the fundamental mode, first overtone and a high-order (9th) radial mode can lead us to the correct explanation of the Blazhko effect (Buchler & Kolláth, 2011). Several months ago Zoltán Kolláth succeeded in calculating a model light curve resembling Blazhko modulated brightness variations.

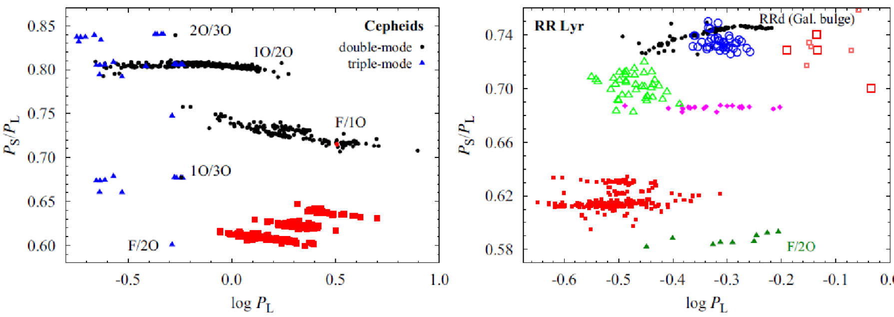

Figure 2. The Petersen diagram for Cepheids (left) and RR Lyrae stars (right) (Smolec et al., 2017).

Double-mode pulsation and nonradial modes are also present in some RR Lyr type variables (Moskalik, 2013). Among the double-mode RR Lyrae variables in the Magellanic Clouds, Soszyński et al. (2016) identified anomalous RRd pulsators, which are characterised by unusual period ratios and modal amplitudes.

Based on Kepler and CoRoT data, new dynamical phenomena have been discovered: period doubling and extra modes in all RR Lyraes pulsating in the first radial overtone, in all double-mode RR Lyraes and all Blazhko modulated fundamental pulsators (Netzel et al., 2015). These additional modes are non-stationary and their frequency ratios are concentrated in narrow intervals (see Fig. 2., right panel). The existence of extra nonradial modes is similar to the phenomenon discussed in Section 4.

Another important aspect of the current RR Lyrae research is the quest for finding binaries among these old pulsators. There is only one undoubted case: TU UMa (Liška et al., 2016), unlike Cepheids in our Galaxy where the occurrence of binaries exceeds 60%. The list of suspected binaries among RR Lyrae stars can be found in the online data base maintained by Liška & Skarka.

7. Telescopes, targets, tasks

Observation of pulsating variable stars needs patience and a huge amount of time. Therefore small (up to 1.5 m diameter) telescopes are used for carrying out photometric observations of such variables. Databases of various photometric sky surveys also offer an opportunity to study individual pulsating variable stars or a group of them.

Table 2. Space telescopes used for, or dedicated to photometry.

Mission (duration)	Aperture (cm)	Band (nm)	Remarks
IUE (1978-1996)	45	wide	Fine Error Sensor, no calibration
			0.03; var.; var.; targets for UV spectra
Hipparcos (1989-1993)	29	400-800 (Hp)	Tycho B_T: 350-500 nm; V_T: 460-600 nm
			0.02; 30-380; 3 years; 118 000 (Tycho: 2.5×10^6)
HST (1990-)	240	460-700	Fine Guidance Sensor
			0.001; var.; var.; millions
WIRE (1999-2011)	5.2	$V + R_{\mathrm{J}}$	star tracker
			0.005; $> 10^3$; 21 d; 200 bright stars
INTEGRAL (2002-)	5	Johnson V	Optical Monitoring Camera
			0.04; var.; var.; $> 10^3$
Coriolis (2003-2011)	1.3	wide	on board SMEI satellite
			0.02; $> 10^3$; years; all naked-eye stars
MOST (2003-2014)	15	380-800	limited field (CVZ)
			0.0001; $> 10^3$; up to 60 d; 5000 bright stars
CoRoT (2006-2012)	27	350-1000	very limited field
			0.0001; $> 10^5$; 0.5 year; 120 000
Kepler (2009-2013)	95	400-900	very limited field
			0.00003; $> 10^5$; 4 years; 150 000
BRITE (2013/2014-)	3	550-700	5 satellites: 3 in blue, 2 in red band
		or 390-460	0.001; $> 10^3$; 30-180 d; $\sim$1000 bright stars
Gaia (2013-)	68	330-1050 (G)	G_{BP}: 330-680 nm; G_{RP}: 640-1050 nm
			0.001-0.020; $\sim$70; >5 years; 1.6 billion
K2 (2014-2018)	95	400-900	small fields along the Ecliptic
			0.0005; 10^5 ; 80 d; 350 000
TESS (2018-)	4×10.5	600-1000	large field of view
			0.0005; $> 10^4$; 27 d; 200 000
CHEOPS (2019-)	30	400-1100	to be launched
			0.00002; n.a.; n.a.; bright exoplanet host stars

In addition to ground-based equipments, space telescopes dedicated to, or used for, stellar photometry (see Table 2) also produce a large amount of time series photometric data. The typical accuracy (in magnitudes), typical number of observations per target, length of the data series, and the approximate number of the observed stars are also listed in the second line of the remarks column of Table 2, for each space project. The advantage of space photometric data is twofold: their accuracy is much better than that of ground-based photometry and the time series is uninterrupted, or there are only short gaps. This latter feature is important for identifying the oscillation frequencies present in the observed star.

In view of the tremendous number of recently discovered new variable stars and the ongoing survey of the ESA's astrometric space probe, Gaia, the chance of revealing new variables during our own observations is extremely low. Observers with small telescopes cannot compete with the discovery efficiency of the LSST, either (LSST Science Collab., 2012). However, projects aimed at studying carefully selected individual pulsating variables can be very productive. A not exhaustive list of the features to be investigated from the observational data is as follows:

- the value of the pulsation period can be updated using the $O - C$ method, if prior photometric data are available;
- from detailed photometric study of individual variables one can point out additional periodicities, perform a mode identification, discover slightly excited non-radial (or radial) modes;
- pulsating variables in binary systems can be especially useful targets because of chance of revealing interactions of binarity and pulsation phenomena;
- for Cepheids and RR Lyrae stars, the atmospheric metallicity can be determined from the shape of the light curve via Fourier decomposition (Klagyivik et al., 2013).

If photometric data are insufficient for a reliable analysis, an in-depth spectroscopic study with a larger telescope can be instrumental. In such cases a cooperation between several telescopes/observatories is beneficial.

Many other interesting facts on pulsating variable stars are discussed in detail in the recent handbooks written by Aerts et al. (2010), Balona (2010), Catelan & Smith (2015), and Percy (2007), as well as in the conference proceedings edited by Suárez et al. (2013).

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