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Pulsating stars – plethora of variables and observational tasks

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Abstract. Developments of this far-reaching research field are summarized from an observational point of view, mentioning important and interesting phenomena discovered recently by photometry of stellar oscillations of any kind. A special emphasis is laid on Cepheids and RR Lyrae type variables.

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

1. Introduction

Variable stars are astrophysical laboratories. Pulsating stars provide us with information on the internal structure of the stars and stellar evolution as testified by their position in the Hertzsprung-Russell (H-R) diagram. Hot and cool oscillating stars, and luminous and low luminosity pulsators are also found in various parts of the H-R diagram (Fig. 1). Several types of luminous pulsators are useful distance indicators via the period-luminosity (P-L) relationship.

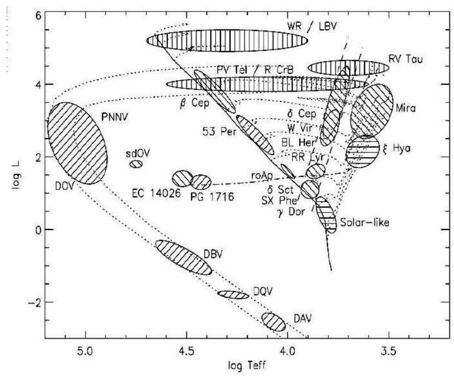

Figure 1. H-R diagram showing the location of various types of pulsating variables (Jeffery, 2008a).

Table 1. Classification of pulsating variable stars.

Type	Design.	Spectrum	Period	Amplitude mag.	Remark*
Cepheids	DCEP	F-G Iab-II	1-135 d	0.03-2	
	DCEPS	F5-F8 Iab-II	<7 d	<0.5	1OT
BL Boo	ACEP	A-F	0.4-2 d	0.4-1.0	anomalous Cepheid
W Vir	CWA	FIb	>8 d	0.3-1.2	
BL Her	CWB	FII	<8 d	<1.2	
RV Tau	RV	F-G	30-150 d	up to 3	
	RVB	F-G	30-150 d	up to 3	variable mean brightness
RR Lyr	RRA	A-F giant	0.3-1.2 d	0.4-2	
	RRC	A-F giant	0.2-0.5 d	<0.8	1OT
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, high-order 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	
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 mag.	Remark*
53 Per		O9-B5	1-3 d		NR
β Cep	BCEP	O6-B6 III-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?

Table 1 is an overview of different types of pulsating variables. The underlying physical mechanism exciting stellar oscillations can be different for various pulsators. The General Catalogue of Variable Stars (GCVS, Samus et al., 2009) lists 33 types and subtypes of pulsating variables, while the International Variable Star Index (VSX) at the AAVSO knows 53 different (sub)types.

Another aspect of the classification is the ambiguity due to the simultaneous presence of more than one type of variability. There are numerous pulsating stars among eclipsing variables, as well as rotational variability can be superimposed on stellar oscillations. Pulsation can be excited in certain cataclysmic variables, and erratic variability is typically present in oscillating pre-main sequence stars. From the point of view of astrophysics this is favourable, but encumbers the analysis and interpretation of the observational data.

Time consuming photometry of pulsating variables is a realm of small telescopes. The temporal coverage (duration of the time series) is critical for studying multiperiodicity, changes in frequency content, modal amplitudes, etc.

The accuracy of photometry is varying, it depends on the telescope aperture, detector quality, astroclimate, etc. Millimagnitude accuracy can be easily achieved with ground-based equipments, while the accuracy of photometry from space is up to micromagnitudes. Figure 2 shows an excellent sample light curve of LR UMa, a DSCT type pulsator obtained with a 1 m telescope (Joshi et al., 2000). (The abbreviated designation of various types is found in the 2nd column of Table 1).

Depending on the observer's experience and capabilities, one may choose observational targets from a wide range of amplitudes, from microvariables to large amplitude pulsators, while the range of periodicity embraces the shortest values of seconds to the longest ones, several years.

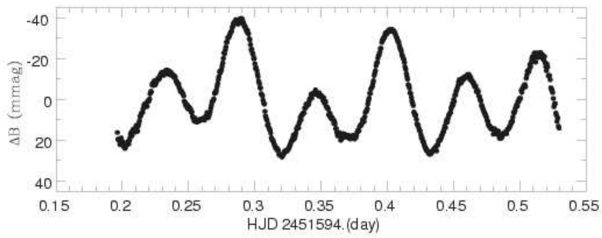

Figure 2. A very low-noise light curve of a short-period pulsator LR UMa (Joshi et al., 2000).

In July 2013, there were 47811 variables catalogued in the GCVS, among them 8533 RR Lyraes, 8098 Miras, 932 classical Cepheids, 762 δ Sct variables, 414 Type II Cepheids, 209 β Cep variables, 85 γ Dor stars, and 80 white dwarf pulsators. A smaller number of variables known to belong to a certain type, however, does not necessarily mean that the given type of pulsating variables is less frequent, some kind of variability is not easy to discover. Moreover, massive photometric surveys, e.g., ASAS (Pojmanski, 2002), OGLE (Szymański, 2005), MACHO (Alcock et al., 1999), WASP (Pollacco et al., 2006), and Pan-STARRS (Burgett & Kaiser, 2009) resulted in revealing thousands of new variables not catalogued in the GCVS.

2. Remarkable behaviour of various pulsating variables

In this section several interesting phenomena observed recently in various types of pulsating stars are described.

The γ Doradus and δ Scuti stars are particularly useful for studying stellar structure and testing related theoretical models via stellar oscillations (asteroseismology). The GDOR stars pulsate in high-order g-modes with periods of order 1 day, driven by convective blocking at the base of their envelope convection zone. The DSCT stars pulsate in low-order g- and p-modes with periods of order 2 hours, driven by the κ mechanism operating in the He II ionization zone. Theory predicts an overlap region in the H-R diagram between instability regions, where hybrid stars performing both DSCT and GDOR type pulsations should exist. Before the launch of Kepler spacecraft, only four such hybrid pulsators were known. From the period analysis of early Kepler data performed for more than 200 pulsators Grigahcéne et al. (2010) found very rich frequency spectra and conclude that essentially all of the stars show frequencies in both the DSCT and the GDOR frequency range.

The DSCT pulsation can be also coupled with solar-like oscillations excited by envelope convection, as discovered in the case of HD 187547 by Antoci et al. (2011).

Even pre-main sequence stars located in the classical instability strip can pulsate, resulting in superposition of erratic and periodic components of stellar variability. As an example, the study of pre-main sequence pulsators in the young clusters IC 4996 and NGC 6530 is mentioned (Zwintz & Weiss, 2006).

A particularly interesting DSCT pulsator is WASP-33, being the host star of an extrasolar planet with an orbital period of 1.21987 days (Herrero et al. 2011). None of the observed pulsation frequencies, nor their low order linear combinations, are in close resonance with the orbital frequency (Kovács et al. 2013). Stability of the oscillation frequencies and amplitudes is well worth studying on a longer time scale.

Discovery of DSCT and GDOR pulsation was even discovered in Ap stars from Kepler data (Balona et al., 2011). Such periodic pulsation of Ap stars was unknown before. On the contrary, rapid oscillations in Ap stars have been known for decades, but their cause have not been clarified yet. The presence of pulsation in Ap stars has to do with the internal stellar magnetic field. About 40 roAp stars are known, i.e., not all Ap stars are rapid pulsators. Not oscillating Ap stars (noAp stars) occupy a similar part of the H-R diagram as the roAp stars.

There is a wide variety of pulsating stars among hotter, B type stars. Here again, one can find hybrid pulsators. The 'classical' β Cephei pulsation can be coupled with either SPB or Be type variability. In the case of pulsation of Be stars, long-term coherent photospheric oscillations may be present, accompanied with quasi-periods of circumstellar origin due to a mass ejection episode in the rapidly rotating hot star, as in the of HD 50064 (Aerts et al., 2010b). Another kind of hybrid pulsation is the simultaneous presence of BCEP and SPB type oscillations in the same stars: in the case of γ Peg, a large number of high-order g-modes, low-order p-modes and mixed modes have been detected by Handler et al. (2009).

Slow pulsation of B stars, i.e. the SPB pulsation is not a rare phenomenon, though its discovery is not easy. The precise and homogeneous Hipparcos photometry was instrumental in revealing a large number of SPB pulsators, and more recently McNamara et al. (2012) found dozens of new SPB variables in the Kepler field. SPB pulsation may be present among pre-main sequence variables as well (Gruber et al. 2012).

Even a supergiant B star may show SPB type variability as revealed in HD 163899 (Saio et al., 2006) from MOST photometry. This is surprizing and needs an appropriate pulsation model. Another new type of variability among B stars was discovered by Mowlavi et al. (2013) who found a number of new variable stars between the red edge of SPB instability region and the blue edge of DSCT stars, where no pulsation is predicted to occur based on the existing stellar models.

Pulsation is present in the most luminous stars, see the light curve of the luminous blue variable (LBV) AG Car in Aerts et al. (2010a).

The least luminous stars can also pulsate in a variety of locations of the white dwarf and subdwarf regions of the H-R diagram: the ZZ Cet type pulsation of white dwarfs has been known since 1968, more recently discovered types are GW Vir (1979), V777 Her (1982), while the types of subdwarf pulsators are V361 Hya (1997) and V1093 Her (2002). Moreover, DW Lyn type (2002) is a hybrid of V361 Hya and V1093 Her type pulsations.

There are less than 15 extreme He-stars known to pulsate in our Galaxy (PV Tel, BX Cir types, Jeffery, 2008b). Study of such variables are informative on late stages of stellar evolution.

RCRB stars falling within the classical instability strip also pulsate, including the archetype R CrB itself (Rao & Lambert, 1997). Crause et al. (2007) put forward convincing evidence that the decline events (i.e., the mass-loss episodes) occurring in RCRB variables are synchronized to the atmospheric oscillations.

The peculiar variable star FG Sge (a post-AGB central star of a planetary nebula) also showed periodic pulsation while the temperature of its false photosphere was appropriate during the rapid crossing of the instability strip and before becoming a cool RCRB variable (Jurcsik & Montesinos, 1999). This sequence of events was a stellar evolutionary episode on a human time scale.

There are numerous pulsating variables among red stars, as well. Some of the Mira variables are also famous of undergoing a rapid evolutionary episode of a He-shell flash, including T UMi (Szatmáry et al., 2003) and R Cen (Hawkins et al., 2001). The pulsation period of these stars is noticeably decreasing from one cycle to the other, accompanied by a secular decrease of the pulsation amplitude. Hawkins et al. (2001) also revealed a correlation between the instantaneous period and semi-amplitude of the pulsation of R Cen. Other cases of secular evolution observed in the pulsation of Mira variables are listed by Templeton et al. (2005).

Pulsating stars in the post-AGB phase of stellar evolution, e.g. RV Tau type variables also show interesting phenomena in their photometric behaviour (Kiss et al., 2007).

3. Importance of binarity among pulsating variables

Binarity is important in variable star research: both eclipsing and cataclysmic phenomena are caused by the presence of a companion star. In the study of pulsating variables, binarity provides an additional aspect to be taken into account in interpreting the observed variability.

On the one hand, a luminous companion can decrease the observable photometric amplitude of the pulsating component, contributing to the wide range of amplitude of Cepheids observed at a given pulsation period. On the other hand, a close (and not necessarily luminous) companion can even trigger stellar oscillations in the other star of the binary system. This is the case of the ‘heartbeat’ variable, KOI-54 (HD 187091) discovered by Welsh et al. (2011) in the Kepler field (Fig. 3). There is a whole class of eccentric binaries in which pulsations are excited tidally (Thompson et al., 2012).

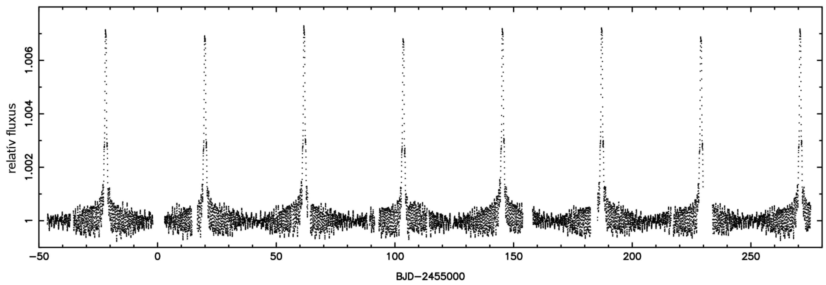

Figure 3. Light curve of the heartbeat variable KOI-54 (HD 187091) (Welsh et al., 2011).

Another kind of externally triggered pulsation was observed in the symbiotic nova RR Tel preceding its eruption in 1948 (Robinson, 1975).

Long-period variations in the mean brightness of RV Tauri stars (RVB subtype) are also caused by the binarity of these pulsators.

Pulsating variables in binary systems can show apparent period changes owing to the light-time effect caused by the orbital motion. Such effect was revealed in the $O-C$ diagram of different types of pulsators, e.g., the archetype BCEP star β Cep (Pigulski & Boratyn, 1992), the DCEP variable AW Per (Vinkó, 1993), the DSCT star SZ Lyn (Derekas et al., 2003), the SXPHE star CY Aqr (Sterken et al., 2011), and the SPB variable HD 25558 (Sódor et al., in preparation). The light-time effect is instrumental in determining orbital elements of the given binary system. In the previous list, HD 25558 is a unique system whose both components are SPB variables.

Binarity is an important aspect for the calibration of the P-L relationship. On the one hand, the photometric contribution of the companion star has to be removed when determining the luminosity of the pulsator involved in the calibration procedure. On the other hand, pulsating stars in binaries with known orbital elements are useful calibrators on their own right.

4. Strange behaviour of classical Cepheids

Astronomy textbooks usually refer to Cepheids as regular radial pulsators with strongly repetitive light curves. However, recently it turned out that classical Cepheids are not perfect astrophysical clocks. V1154 Cyg, a first overtone pulsator, the only Cepheid in the Kepler field shows cycle-to-cycle variations in both the shape of its light curve and pulsation period (Derekas et al., 2012). This behaviour needs an astrophysical explanation. Though the instantaneous pulsation period flickers (Fig. 4), the average period remains stable on the time scale of several decades.

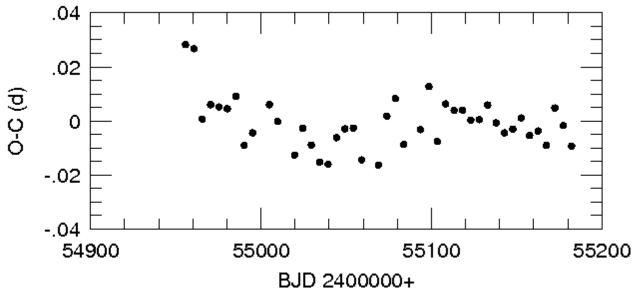

Figure 4. $O-C$ diagram of the Cepheid V1154 Cygni based on the Kepler photometry (Derekas et al., 2012).

Stellar evolution has its impact on the pulsation period of Cepheids, as well. Rapidly evolving long period Cepheids sometimes show spectacular changes in their pulsation period, and erratic fluctuations superimposed on the secular period variation (Fig. 5).

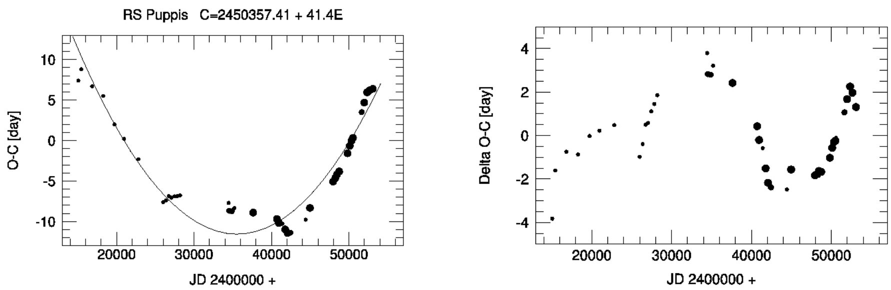

Figure 5. $O-C$ diagram of the long-period Cepheid RS Puppis (left) and the residuals after subtracting the fitted parabola (right) (Szabados, unpubl.).

Subtle period changes can be pointed out from long series of high-quality photometric observations. The definite phase jump in the pulsation of the peculiar Cepheid Polaris is especially noteworthy (Turner et al., 2005). This jump may be a result of a proximity effect in the binary system. The origin of the secular variation in the pulsation amplitude of Polaris is, however, a mystery.

An additional periodicity is frequently present in Cepheids: hundreds of double-mode Cepheids are known in both Magellanic Clouds. In these galaxies there exist Cepheids pulsating simultaneously in three radial modes. Slight excitation of nonradial modes was also found in 9% of the first overtone Cepheids in the Large Magellanic Cloud, and signs of the Blazhko effect (a typical phenomenon of RR Lyrae type pulsators) have also been revealed among Magellanic double-mode Cepheids (Moskalik, 2013). In our Galaxy, there is only one known Cepheid showing the Blazhko effect: V473 Lyr (Molnár et al., 2013).

5. RR Lyrae variables

In addition to their large amplitude periodic pulsation, RR Lyr type variables also show various other effects worthy of studying in detail. The most frequently occurring phenomenon is the Blazhko effect, a slow, cyclic (not periodic) modulation of the light curve (both amplitude and phase) observed in both RRA and RRC variables (Fig. 6). In spite of the fact that Blazhko effect occurs in about 50% of the field RRab stars, its origin is a century-long enigma. Although several models have been elaborated (a magnetic oblique rotator, a nonradial resonant rotator, interaction of shock waves, cycles in the convection), none of them can be accepted as a real explanation.

An up-to-date list of RR Lyrae variables in the Galactic field known to exhibit Blazhko effect has been compiled by Skarka (2013). This catalog of Blazhko modulated RR Lyr stars contains 242 variables including 8 stars with more than one (incommensurable) modulation period, and 4 stars whose modulation period strongly varies.

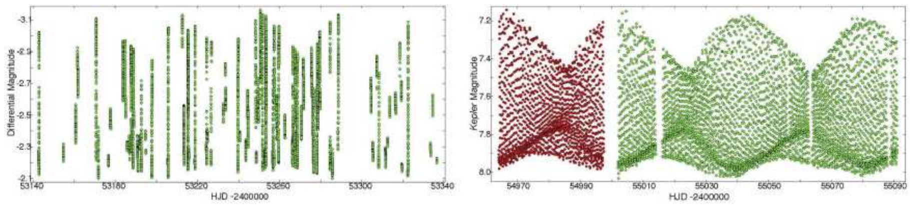

Figure 6. Light curve of RR Lyr from ground-based (left) and space-based (Kepler) data (right)(adapted from Kolenberg, 2011).

Double-mode pulsation and nonradial modes are also present in some RR type variables (Moskalik, 2013).

Based on Kepler data new dynamical phenomena have been discovered: period doubling (in RR Lyr by Molnár et al., 2012), triple-mode pulsation (in V445 Lyr by Guggenberger et al., 2012; in RR Lyr by Molnár et al. 2012), and high-order resonances (in RR Lyr by Molnár et al. 2012). 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 present in RR Lyrae variables.

6. Plethora of optical telescopes

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

Mission	Duration	Aperture (cm)	Remark
IUE	1978-1996	45	FES, no calibration
Hipparcos	1989-1993	29	Hp wide-band magnitude
HST	1990-	240	FGS
WIRE	1999-2011	5.2	star tracker
INTEGRAL	2002-	5	OMC, Johnson V
Coriolis	2003-	1.3	SMEI instrument
MOST	2003-	15	limited field (CVZ)
CoRoT	2006-2012	27	very limited field
Kepler	2009-2013	95	very limited field
BRITE	2013	3	blue & red bands

Figure 1 in the paper by Mountain & Gillett (1998) (not repeated here) shows the temporal increase of the cumulative mirror area of optical astronomical telescopes. Owing to the enormous progress in engineering, there exist giant telescopes in service of astronomy, yet small aperture telescopes contribute overwhelmingly to the recent steep increase. These small telescopes (up to 1.5 m diameter) are ideal instruments for carrying out photometric observations of variable stars.

In addition to ground-based equipments, there exist photometric space telescopes or other space telescopes also used for stellar photometry (see Table 2). Most of them have a small aperture, and it is favourable that their photometric data are accessible in most cases.

7. Plethora of new variables

Although the catalogued variable stars offer a wide choice for photometric observers, there are many recently discovered pulsating variable stars whose variability was revealed in massive photometric surveys, e.g., ASAS, OGLE, MACHO, VVV, and these variables have not been included in the GCVS yet.

Photometric data bases of major ground-based sky surveys such as Catalina Sky Survey (Drake et al., 2009), Pan-STARRS, Sloan Digital Sky Survey (Abazian et al., 2003), LSST (LSST Science Collaborations, 2009) are or will be ample sources of new targets with variable brightness (including pulsating variables) for thorough photometry with small or medium aperture telescopes.

In the coming years, discovery of a tremendous number of new variable stars is envisaged. Gaia, the ESA's astrometric space probe, will collect photometric data of a billion stars from 2014 on. As a result, discovery of 18 million new variable stars is expected from its data base. The estimated number of pulsating variable stars to be observed by Gaia is as follows (Eyer & Cuypers, 2000): 2000-8000 Cepheids (9000 according to Windmark et al., 2011), 70000 RR, 60000 DSCT, 140000-170000 Miras, 100000 SR stars, 3000 BCEP variables, 15000 SPB pulsators, etc.

8. Variety of observational tasks and their outcome

It is not necessary to be involved in a long-term observational project. Even a single light curve provides useful pieces of information: 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), and the value of the pulsation period can be updated with the help of the $O-C$ method, if prior photometric data are available.

From a data set obtained during one season one can determine the type of variability for newly revealed variable stars. Even discovery of a new type is possible, e.g., brown dwarf pulsation is predicted by theory (Palla & Baraffe, 2005) but it has been unobserved yet.

From longer data sets, i.e. detailed photometric study of individual variables, one can point out additional periodicities, perform a mode identification, discover slightly excited non-radial (or radial) modes. Existence of triple-mode radial pulsators has been an unexpected recent discovery (see e.g., Wils et al., 2008 and Moskalik, 2013).

Observations of pulsating variables in binary systems can be especially fruitful because of interactions of binarity and pulsation phenomena.

The astrophysical interpretation of the photometric data includes the determination of physical properties of the given star(s) from the analysis of the light variations: evolutionary state, internal structure, metallicity, rotation, presence of companion(s), etc.

It may happen that photometric data are insufficient for a reliable analysis, yet the light variations indicate that the given pulsator deserves an in-depth (spectroscopic) study with a larger telescope. Cooperation between several telescopes/observatories is beneficial in any case.

For further information about pulsating variable stars, the following books are recommended: Aerts et al. (2010a), Balona (2010), Percy (2007), and Suárez et al. (2013) in which a lot more interesting phenomena have been discussed.

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