Highlights of stellar astrophysics

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This is a review on advances in stellar astrophysics achieved by astronomers affiliated to Polish astronomical institutions in years 2017 – 2019.

Over the last three years Polish-based astronomers had a significant contribution to the development of stellar astrophysics. Undertaken investigations referred to the stellar objects on various stages of evolution, including normal stars, pre-main sequence stars, and evolved objects. Most of the published papers are on pulsating stars, their properties and applications to the galactic structure studies. Here, I present all important results from the years 2017 – 2019.

1 Studies of enigmatic star FU Orionis

Pre-main sequence stars are difficult objects to study due to their irregular behaviour. FU Orionis represents a group of young stellar objects characterized by a rise in brightness by about 4 – 6 mag and slow decline several months after. Observations of FU Orionis gathered by MOST satellite continuously for 55 days and simultaneously obtained ground-based multi-colour data were compared to create a model of the object. Siwak et al. (2018), in the article entitled *Insights into the inner regions of the FU Orionis disc*, show that the observed light variations arise from rotational revolution of disc inhomogeneities located between 16 and $20\,R_{\odot}$. The variations are due to changing visibility of plasma tongues revolving in the magnetospheric gap or due to hotspots.

2 An important message from early-type main-sequence pulsators

Bright pulsating B-type stars are among the targets of the Austrian-Canadian-Polish constellation of six BRITE nano-satellites. In the work *Seismic modelling of early B-type pulsators observed by BRITE I. θ Ophiuchi*, Walczak et al. (2019) analyse photometric data for hierarchical triple system θ Ophiuchi. In this system, component Aa is a B2IV star, component Ab is a low-mass star on a 56.71 day orbit, while component B is a B5 star on a wide, ≈ 100 year orbit. The detection of 26 modes (mainly high-order g-modes) confirm that θ Ophiuchi Aa is a hybrid β Cep/SPB pulsator with a mass of $8.4 - 8.6\ M_{\odot}$.

The work *What Have We Learnt About B-Type Main Sequence Pulsators from the BRITE Data?* by Daszyńska-Daszkiewicz et al. (2018) is a call for revision of opacity values. Studies of early-type stars ν Eridani, 12 Lacertae, γ Pegasi, θ Ophiuchi, κ Scorpii, and α Lupi indicate that the opacities should be higher in the case of hot (Z-bump) pulsators, even by a factor two.

3 A new map of the Milky Way from classical Cepheids

Cepheid variable stars are an often topic of several publications in 2017 – 2019. Udalski et al. (2018) presented the OGLE Collection of Galactic Cepheids. The OGLE survey more than doubled the number of known Galactic classical Cepheids. 1300 such variables, out of the total of 2543, have been found by the Polish survey. Skowron et al. (2019) have used the classical Cepheids to draw a three-dimensional map of the Milky Way. This is the first real map of our Galaxy since precise distances to the individual objects are determined. For the first time, the young population of the outer Galactic disc have been explored. The data were used to investigate the geometry of the disc (its warping and flaring) and to perform an age tomography. The work appeared in Science magazine and received a historic top 100 attention. A cross-match of the OGLE collection of Cepheids with Gaia Data Release 2 have allowed Mróz et al. (2019) to use the information on proper motions and radial velocities for 773 stars and to construct the rotation velocity curve of the Milky Way. The rotation curve at Galactocentric distances $4 < R < 20\,\mathrm{kpc}$ is almost flat with a mild gradient of $-1.34 \pm 0.21\,\mathrm{km\,s^{-1}kpc^{-1}}$.

For over twenty years the OGLE project regularly monitors the area of the Magellanic Clouds. As a result, Soszyński et al. (2019b) have published the *Final Release of the OGLE Collection of Cepheids and RR Lyrae Stars in the Magellanic System.* The most important message is that a century-long search for classical Cepheids in the Magellanic Clouds has just been completed. According to the census, the Clouds contain 9650 classical Cepheids. OGLE has also detected 343 type II Cepheids, 278 anomalous Cepheids, and 47 828 RR Lyrae-type stars over 765 square degrees covering the Magellanic System.

Classical Cepheids and RR Lyrae stars were used to trace the three-dimensional structure of the whole Magellanic System in young ($< 300\,\mathrm{Myr}$) and old ($> 10\,\mathrm{Gyr}$) populations, respectively. Recently, Jacyszyn-Dobrzeniecka et al. (2017) showed that Magellanic Clouds' halos overlap. There is a bridge between the Clouds in the young population, but not in the old one.

4 Key results on type II Cepheids

A few recent papers concentrated on the physical properties of Cepheids. Smolec et al. (2018) published a paper on *Diversity of dynamical phenomena in type II Cepheids of the OGLE collection.* They report on the detection two BL Herculis-type stars pulsating simultaneously in the fundamental mode and in the first overtone. Previously, only fundamental-mode type II Cepheids were known. The authors show that alternating minima of different depth or the period-doubling effect appears in W Virginis-type stars at the period slightly above 15 days and continues smoothly to longer periods of RV Tauri-type stars. Soon after, Soszyński et al. (2019a) reported on the discovery of the first two *Type II Cepheids Pulsating in the First Overtone from the OGLE Survey.* Visually, light curves of all first-overtone Cepheids (classical, type II, and anomalous Cepheids) show rounded minima. According to the pulsation theory type II Cepheids must be rare (only two such pulsators are known among 75 million monitored stars) and are more massive than thought before ($> 0.85\,\mathrm{M_\odot}$). A problem with the latter property is that it implies a luminosity much higher than observed.

Publications by Pilecki et al. (2018b) and Pilecki et al. (2018a) refer to intrinsic properties of Cepheids in binary systems. In the work entitled *The dynamical mass and evolutionary status of the type-II Cepheid in the eclipsing binary system OGLE-LMC-T2CEP-211 with a double-ring*, the authors, for the first time, determine the mass and the radius of such type of a pulsator. This is a peculiar W Virginis-type variable of 0.64 ± 0.02 M$_\odot$ and 25.1 ± 0.3 R$_\odot$. They conclude that this type of pulsators seem to be products of evolution in binary systems. From the other work, *The Araucaria Project: High-precision Cepheid Astrophysics from the Analysis of Variables in Double-lined Eclipsing Binaries*, we can learn that the so-called p-factor is not a pure function of the period, but it depends on other stellar parameters, such as the mass, radius, and the amplitude of radial velocity variations.

5 A new precise distance to the LMC

One of the recent hits was the Nature paper *A distance to the Large Magellanic Cloud that is precise to 1%* by Pietrzyński et al. (2019). The value of $49.59 \pm 0.09_{\text{statistical}} \pm 0.54_{\text{systematic}}$ kpc was obtained based on observations of 20 eclipsing binaries with late-type components. The major step that allowed to achieve such precision was a new calibration of the surface brightness–colour relation for nearby red clump giants. The used eclipsing binaries from the LMC are detached systems with red clump giants as primary components.

6 Results of the studies of various binary stars

A unique eclipsing system is the topic of the publication by Skowron et al. (2017): *OGLE-LMC-ECL-09937: The Most Massive Algol-Type Binary System with a Mass Measurement Accurate to 2%.* The components have the following masses: $M_1 = 21.04 \pm 0.34$ M$_\odot$, $M_2 = 7.61 \pm 0.09$ M$_\odot$. This object is a good candidate for a future double neutron star system.

In their work, Dubus et al. (2018) conducted a test of the disc instability model of cataclysmic variables. They verified the separation of cataclysmic variables into nova-like and dwarf nova objects depending on the orbital period and mass transfer rate from the companion. For a sample of about 130 cataclysmic variables they used parallax distances from the Gaia DR2 catalog to derive the average mass transfer rates. In conclusion, after 36 years the dwarf-nova disc instability model once again passed the test of observations: dwarf novae (nova-likes) are placed in the unstable (stable) region of the orbital period–mass transfer rate plane.

The work by Iłkiewicz et al. (2019) informs about object *LMC S154: the first Magellanic symbiotic recurrent nova.* Archival data show that before 2015 the nova erupted also in the 1940s and 1980s.

Heartbeat stars form an interesting group of astrophysical targets. These objects are eccentric binary systems whose one of the component or both components experience noticeable tidal distortions during the periastron passage. The changed shape of the star is seen as low-amplitude heart-beat-like variations in the light curve. Pigulski et al. (2018) report the discovery of *τ Ori and τ Lib: Two New Massive Heartbeat Binaries.* Based on photometric data from BRITE satellites and ground-based spectroscopic follow-up observations, the authors report the following parameters of τ Ori: the orbital period of the system of about 3.45 days, mass of the primary component of about $6.6\,M_\odot$ and the secondary component of $5.3\,M_\odot$.

7 BLAPs — a new class of variable stars

The discovery of a completely new type of objects is announced in Nature Astronomy article: *Blue Large-Amplitude Pulsators as a new class of variable stars* by Pietrukowicz et al. (2017). The variables were found among hundreds of millions of stars observed by the OGLE survey. They have amplitudes of 0.2 – 0.4 mag at periods of 20 – 40 min, which is extreme. Follow-up spectroscopy confirmed that the stars are hot (with effective temperatures $T_{\rm eff}$ of around 30 000 K) and the observed variations are caused by intrinsic changes, that is pulsations. The new variables, BLAPs, resemble classical pulsators but at $T_{\rm eff}$ at which pulsations are driven due to the presence of iron-group elements. BLAPs are likely $\approx 0.3\,M_\odot$ helium-core pre-white dwarfs with inflated envelopes. Such stars cannot be produced in the normal process of single star evolution. They seem to be a result of interacting binary evolution. These stars remain mysterious.

To summarize, in the period 2017 – 2019, Polish-based astronomers were the first or at least the second authors of many publications in the area of stellar astrophysics. Here, I reported results of 16 most important journal articles and 2 conference proceedings. Three of the papers appeared in top journals: Science, Nature, and Nature Astronomy.

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