HABILITATION SUMMARY

1. Name: **Paweł Pietrukowicz**

2. List of all scientific degrees:

– **Master of Science (MSc)** in astronomy, obtained on 19 June 2002
at the Faculty of Physics, University of Warsaw, Poland, supervisor Prof. Janusz Kałużny,

– **Doctor of Philosophy (PhD)** in astronomy, obtained on 30 March 2007
at Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences, Warsaw, Poland,
PhD thesis: *Poszukiwanie nowych karłowatych w wybranych gromadach kulistych projektu CASE / Searching for dwarf novae in selected globular clusters*, supervisor Prof. Janusz Kałużny.

3. Employment:

1.10.2002 – 30.03.2007: PhD student at Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences in Warsaw, Poland

1.04.2007 – 30.09.2007: programmer at Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences in Warsaw, Poland

1.10.2007 – 30.09.2009: postdoctoral researcher at Departamento de Astronomía y Astrofísia, Pontificia Universidad Católica de Chile, Santiago de Chile

1.10.2007 – 30.09.2010: postdoctoral researcher at Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences in Warsaw, Poland (lay-off in the period of 1.10.2007 – 30.09.2009)

1.10.2010 – present: postdoctoral researcher at Astronomical Observatory, University of Warsaw, Poland

4. Habilitation achievement.

a) Title:

Pulsating variable stars in studies on the Milky Way structure and evolution

b) Publications:

P1: **Pietrukowicz P.**, Udalski A., Soszyński I., Nataf D. M., Wyrzykowski Ł., Poleski R., Kozłowski S., Szymański M. K., Kubiak M., Pietrzyński G., Ulaczyk K., *The Optical Gravitational Lensing Experiment: Analysis of the Bulge RR Lyrae Population from the OGLE-III Data*, The Astrophysical Journal, 2012, 750, 169;

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P2: **Pietrukowicz P.**, Kozłowski S., Skowron J., Soszyński I., Udalski A., Poleski R., Wyrzykowski Ł., Szymański M. K., Pietrzyński G., Ulaczyk K., Mróz P., Skowron D. M., Kubiak M., *Deciphering the 3D Structure of the Old Galactic Bulge from the OGLE RR Lyrae Stars*, The Astrophysical Journal, 2015, 811, 113;

P3: **Pietrukowicz P.**, Dziembowski W. A., Mróz P., Soszyński I., Udalski A., Poleski R., Szymański M. K., Kubiak M., Pietrzyński G., Wyrzykowski Ł., Ulaczyk K., Kozłowski S., Skowron J., *Large Variety of New Pulsating Stars in the OGLE-III Galactic Disk Fields*, Acta Astronomica, 2013, 63, 379;

P4: **Pietrukowicz P.**, Latour M., Angeloni R., di Mille F., Soszyński I., Udalski A., Germanà C., *A Low-Resolution Spectroscopic Exploration of Puzzling OGLE Variable Stars*, Acta Astronomica, 2015, 65, 39.

c) Presentation of research goals, results, and resulting publications.

Our Galaxy, the Milky Way, is formed of billions of stars, interstellar gas and dust, and dark matter. Stars contribute to the mass of the whole Galaxy in a small fraction, but they are visible at large distances. Therefore, they are very useful in studies on the Milky Way structure and evolution. Unfortunately, these studies are hampered due to the presence of large amount of dust near the Galactic plane and the location of the Sun close to it. Recently, thanks to the monitoring of millions of stars by wide-field ground-based surveys such as OGLE (the Optical Gravitational Lensing Experiment) and the special space mission Gaia, the picture of our Galaxy becomes to be more clear.

By 1990s the picture was very simple. It was known that Milky Way is a spiral galaxy with a central bulge dominated by red giants of an age of a few billion years. Based on the distribution of nearby open clusters and classical Cepheids it was recognized that young objects (from a few million to a few hundred million years old) are present in a thin disk and generally group along stripes, the Milky Way spiral arms. A more pronounced spiral structure emerged from radio observations on the 21 cm neutral hydrogen line (van de Hulst *et al.* 1954). It was also known that both the disk and the bulge are embedded in a large, likely spherically symmetric halo full of old (>10^{10} years) globular clusters and old metal-poor stars. Later, it was recognized that the Milky Way rotation curve is flat (what indicates large amount of dark matter) and the radio source Sagittarius A* represents the central black hole of a mass of a few million solar masses (Wollman *et al.* 1977). Estimation of the distance to the Galactic Center (GC) R_0 is still a difficult task. By averaging distances obtained from different measuring methods Genzel *et al.* (2010) found $R_0 = 8.23 \pm 0.20_{stat} \pm 0.19_{sys}$ kpc. For a long time, a canonical model of the Galaxy formation developed by Eggen *et al.* (1962) was widely accepted. In this model the Galaxy was formed in a rapid radial collapse (~10^8 years) of the initial protogalactic cloud followed by rapid settling of gas into a rotating disk leading to a smooth distribution of stars observable today.

Such a simple picture of the Milky Way was destructed in 1990s after the discovery of a tidally disrupted dwarf galaxy in Sagittarius (Ibata *et al.* 1994) and other streams and overdensities in the Galactic halo. Moreover, some globular clusters turned out to be more complex than it had been thought before. Some clusters are mixtures of multiple populations and probably are disrupted remnants of former dwarf galaxies (*e.g.* omega Centauri, Lee *et al.* 1999). New observations of Galactic halo objects and other galaxies started to favor the hierarchical formation scenario in which large objects are formed from small fragments (Searle & Zinn 1978). Based on observations of stars in the solar neighborhood it was shown that the Galactic disk is composed of two components: thin disk and thick disk (Chiba & Beers 2000). Finally, more and more data indicated the presence of a bar in the central part of our Galaxy.

With the beginning of 1990s the era of large-scale surveys started. Among them were OGLE and MACHO in the optical regime and the near-infrared 2MASS project. An invaluable contribution was brought by the satellite mission COBE. A multiwavelength infrared detector DIRBE onboard COBE was used to map dust emission in the Galaxy. The extinction map published by Schlegel *et al.* (1998) is still very widely used in various studies of objects at Galactic latitudes higher than 10°. Closer to the Galactic equator this maps has to be treated with caution, since the true distribution is still poorly known.

The OGLE project started in 1992 with the main aim to detect gravitational microlensing events and to solve a longstanding problem of the nature of dark matter (Udalski *et al.* 1992). Currently, OGLE is a large-scale variability survey of dense stellar fields in the Milky Way, such as the Galactic bulge and disk, and a separate area of the Magellanic System. Observations showed that the dark matter is not formed of massive compact halo objects (MACHOs). Nevertheless, huge amount of the photometric data from OGLE can be used in studies on selected single objects as well as all populations forming stellar systems such as our Galaxy, the Magellanic Clouds, and star clusters. Observations are conducted from Las Campanas Observatory in the Chilean Atacama Desert. In years 1992–1995 photometric data were collected for a few months per year with the 1.0-m Swope telescope. Since 1996 observations are taken with the dedicated 1.3-m Warsaw Telescope every clear night for the whole year. Since March 2010 the project is in its fourth phase (OGLE-IV, Udalski *et al.* 2015), surveying about 1.3 billion stars in an area of about 3500 square degrees. Previous OGLE phases took place in years 1992–1995 (OGLE-I), 1997–2000 (OGLE-II), and 2001–2009 (OGLE-III). With the launch of each phase a new, larger field of view camera was installed. Most of the observations (about 90%) are taken in the *I* band (central wavelength at 8000 Å, FWHM of 1480 Å), the remaining are taken in the *V* band (5370 Å, 950 Å). The used filters have characteristics closely resembling the standard system *BVI* bands. Therefore, the OGLE photometric data are very well suited to large variety of astrophysical applications.

Since OGLE, from its very beginning, monitored the bulge, it has largely contributed to the knowledge on this component of the Galaxy. A higher than expected number of microlensing events toward the bulge already suggested its elongated shape (Kiraga & Paczyński 1994). Analysis of the observed distribution of red clump stars from three OGLE-I fields located every 5° in Galactic longitude, was presented in Stanek *et al.* (1994). They showed that these stars form a bar inclined by no more than 45° to the Sun–GC line with the closer end at the positive Galactic longitudes. Here it is worth to explain that red clump stars are core helium-burning red giants, 6–10 billion years old, shinning with a constant light. These stars serve as standard candles, since they are numerous, bright, and are characterized by a small scatter of the observed brightness. Rattenbury *et al.* (2007) used this type of stars from OGLE-II to find the axis ratio of the Galactic bar of 10:3.5:2.6, the tilt angle of 24°–27°, and the size of the bar of 3.1–3.5 kpc. Slightly earlier, based on the 2MASS data López-Corredoira *et al.* (2005) found the shape of the bar to be boxy rather than ellipsoidal. Boxy bars are observed in other spiral galaxies. Quite recently, using the OGLE-III data Nataf *et al.* (2010) found that the red clump is split into two components along several sightlines toward the bulge. The difference in brightness reaches about 0.5 mag in the *I* band at latitudes of ±5.7°. This feature is explained that the Galactic bar seen edge-on is X-shaped (McWilliam & Zoccali 2010).

The described above picture of the inner Milky Way refers to the intermediate-age population that currently dominates the mass and luminosity of the bulge. The age of the Galactic bar is estimated to be of about 10 billion years from isochrone fitting to deep (V~29 mag) SWEEPS data collected with the Hubble Space Telescope (Sahu *et al.* 2006). That was in the period of the highest formation rate in the Universe, corresponding to a redshift of z=2. The Galactic bar was likely formed in about 1 billion years (Minniti & Zoccali 2008). It is important to notice that there are also young objects in the bulge, like supernova remnants and classical Cepheids (Matsunaga *et al.* 2011, Dékány *et al.* 2015), and a few million years old nuclear star cluster.

Our Galaxy must have looked completely different in early stages of evolution. It is believed that first stars in the Universe were composed almost only of hydrogen and helium, they were massive and lived for a short period of time. First generation stars or Population III stars have not been detected yet. However, metal-poor stars can be found everywhere in our Galaxy and its vicinity. They are key to understand the process of structure formation in the Universe. Metal-poor stars are classified as Population II stars and they are present in the whole Galaxy, they form the halo and globular clusters. Population II stars can be very old, they could be formed a few hundred million years after the Big Bang. Depending on the initial mass they are on different stage of the evolution. Among Population II stars there are main sequence stars (subdwarfs), red giants, and cooling white dwarfs. Population II subdwarfs and giants cannot be more massive than 0.85 $M_{\odot}$. Otherwise, at the current age of the Universe (13.8 billion years) they would have consumed all their nuclear fuel and would not be bright. It is easy to separate halo stars from other objects in the solar neighbourhood by their speed and elongated orbits around the GC. Young stars (Population I, with an age of up to a few hundred million years) and intermediate-age stars (of up to a few billion years, like our Sun) revolve the Center on roughly circle orbits close to the Galactic plane.

To trace old populations at distances of kiloparsecs or farther out one needs to use the pulsating variables of the RR Lyrae type. These are core helium-burning red giants on the horizontal branch just crossing the main instability strip. Generally, RR Lyrae stars pulsate in the fundamental mode (type RRab) or in the first overtone (type RRc), or these two modes simultaneously (type RRd). Pulsation periods are between 0.2 and 1.0 days, while amplitudes may reach 1.0 mag in the *I* band. Phased light curves of fundamental-mode stars have the characteristic triangle shape with a steep rising branch, while light curves of first-overtone stars are similar to a sinusoid. So far, the mass of none of known RR Lyrae stars has been measured accurately. According to theoretical models RR Lyrae stars have masses between 0.55–0.85 $M_{\odot}$. They have a well estimated absolute brightness (M_V between +0.3 and +0.9 mag, depending on metallicity [Fe/H]), and therefore are widely used for distance measurements within our Galaxy and the Local Group. Unfortunately, it is impossible to estimate the age of a RR Lyrae star more precisely than say that they have >10 billion years (Marconi 2005). It is because we do not know how much matter the star lost through the stellar wind in earlier phases of life.

First RR Lyrae type stars toward the Milky Way bulge were discovered in 1930s. Later, Walter Baade found that this type of stars concentrate toward the GC. This was an evidence that Population II is indeed present in the Galactic bulge (Baade 1946). By 1990s about one thousand RR Lyrae variables were detected in the inner region of the Milky Way. Recent discoveries of bulge RR Lyrae stars have been made mostly by the OGLE survey: 215 variables were found in the OGLE-I fields (Udalski *et al.* 1997), 2713 variables in the OGLE-II fields (Mizerski 2003), 16836 variables in the OGLE-III fields (Soszyński *et al.* 2011), and 38257 variables in the OGLE-IV fields (Soszyński *et al.* 2014). However, first qualitative analyses of the bulge RR Lyrae population were done on a sample of about 1700 variables observed by the MACHO project. This microlensing project was conducted in Mount Stromlo Observatory in Australia in years 1992–1999. Minniti *et al.* (1998) found that the spatial distribution of bulge RR Lyrae stars can be described by the power-law function with an index of –3 and their surface distribution on the sky is flattened along the Galactic plane with a proportion of 10:7. In other work from MACHO, Alcock *et al.* (1998) payed attention that in the inner part of the bulge the RR Lyrae stars seem to trace the red clump bar. It was not obvious, since the results were based on observations covering merely 12 deg^2 in the direction of Baade's Window, a region of relatively low extinction.

Further works on Population II in the inner Galaxy required a much larger coverage of the bulge area and more variables. Such data were obtained by the Polish OGLE team. To be precise, 16836 RR Lyrae variables were detected in an area of 69 deg^2 in OGLE-III (Soszyński *et al.* 2011) and 38257 variables in 182 deg^2 in OGLE-IV (Soszyński *et al.* 2014). I analyzed these collections of variables immediately after completion of the samples. Results were published within a few months after release of the samples. Analyses of the OGLE-III data and later OGLE-IV data appeared in *The Astrophysical Journal* in papers **P1** and **P2**, respectively.

In each case, prior to the analysis of the proper bulge RR Lyrae population the sample had to be cleaned from contaminants, particularly from foreground and background objects. It was done using the color-magnitude (*I vs. V–I*) diagram. In this diagram, due to different extinction in different directions the bulge stars form a sequence along the reddening vector. In the case of the OGLE-III data I did the cleaning for RR Lyrae stars of all types. Also, I had to clean each sample of RR Lyrae stars from globular cluster members. Bulge clusters are not very metal poor and very rarely harbor RR Lyrae variables. In total, a few dozens of such variables had to be rejected from the final samples.

A crucial problem to overtake in the studies on the structure and properties of the Galactic bulge and disk and objects behind the Milky Way is the amount of interstellar dust on the line of sight to the investigated objects, or the problem of proper dereddening. It is well known that dust resides in the Galactic thin disk which scale height (or thickness above the Galactic plane) is estimated to be about 270 parsecs (Jurić *et al.* 2008). The dust is generally located in the spiral arms, where new stars born. Unfortunately, there is no good extinction map at low Galactic latitudes yet, not talking about a three-dimensional version. We do not know how much of the dust is in the bulge itself. Discoveries of young objects in this Milky Way component indicate that close the Galactic plane some clouds of gas and dust are very likely present. Observations of the Galactic bulge objects in the optical regime at latitudes below 1° are practically impossible due an extreme extinction, reaching 30 mag or more in the *V* band. Above this latitude more and more objects emerge from the clouds. Higher above the plane we observe, the reddening gets lower and it is caused by clouds located closer to us than the investigated star. It is very likely that the dust, that obscures the RR Lyrae stars observed in the optical bands by OGLE, is located only in the Galactic disk. At the time of the analysis of the variables from OGLE-III there was no extinction map toward the bulge. First such maps were constructed based on red clump stars soon after that. The only good solution was to assume that properties of the dust are the same in all investigated OGLE-III fields, namely that the reddening vector is the same in each observed direction. Dividing the whole area into fragments did not bring good results. I used the obtained mean ratio of total-to-selective extinction of $R_{I,V-I}$ = 1.080±0.007 to each of the RR Lyrae star. This value is in agreement with the result from OGLE-II ($R_{I,V-I}$ = 1.1, Udalski 2003) and confirms a non-standard extinction toward the bulge in comparison to less dusty high-latitude Galactic regions from the COBE map ($R_{I,V-I}$= 1.4, Schlegel *et al.* 1998).

It is worth to say here a few words on advantages of RRab type variables over RRc type stars in the studies of the Galactic structure. (RRd type variable are very rare and I did not take them into account at all.) The fundamental-mode RR Lyrae variables (RRab stars) with their characteristic triangle or saw-tooth-shape light curves and pulsation periods between 0.3–1.0 days are truly unique. It is very hard to overlook them, what makes the searches for such variables highly complete. Light curves of RRc type variables resemble a sinusoid and their amplitudes are much lower than those of RRab stars. Very often it is hard to distinguish between faint RRc stars and spotted or ellipsoidal variables. Moreover, RRab type variables are on average more frequent and brighter in the *I* band than RRc stars. Finally, there is one more important advantage of RRab variables. Kovács & Zsoldos (1995) found that it is possible to estimate metallicity of RRab stars from their light curve parameters. Jurcsik & Kovács (1996) proposed a simple relation between the metallicity of the star [Fe/H], pulsation period *P*, and Fourier combination $\varphi_{31} = \varphi_3 - 3\varphi_1$ derived from its *V*-band light curve. In the case of the *I*-band OGLE data, I used a relation from Smolec (2005).

My analysis of the metallicity distribution for 10259 RRab stars from OGLE-III have shown that the old bulge population is very homogeneous, or well mixed. The distribution is symmetric with the maximum at $[Fe/H]_{J95} = -1{,}02 \pm 0{,}18$ dex and a dispersion of 0,25 dex on Jurcsik (1995) metallicity scale. Mean metallicities of the bulge RR Lyrae stars seem to be similar in all directions.

As I mentioned earlier, RR Lyrae variables are standard candles with well-known properties. Using period–(absolute brightness)–metallicity relations for the *V* and *I* bands from models in Catelan *et al.* (2004) and the obtained reddening coefficient, I calculated the intrinsic brightness I_0 and distance *d* to each of the bulge variable. In the case of the RRc stars, this procedure gives less accurate results due to the lack of information on metallicity. To obtain the final distance distribution of the RRab sample I had to apply the following two geometric corrections: (1) to project all the stars onto the Galactic plane and (2) to take into account the „cone effect" – that the fields subtend solid angles on the sky with more volume farther away. The obtained distance distribution was very symmetric, confirming a high completeness of the sample. To the data I fit the King (1962) profile, which is widely used in studies of the distribution of stars in clusters. The maximum of the distribution indicates the distance to the GC. Based on the OGLE-III data I found $R_0 = 8.54 \pm 0.42$ kpc, which is in agreement with previous determinations from RR Lyrae stars (*e.g.* Collinge *et al.* 2010: $R_0 = 8.3 \pm 0.7$ kpc) and using other measuring methods (for example, from the motions of stars near the central black hole in Gillessen *et al.* 2009: $R_0 = 8.28 \pm 0.15_{\text{stat}} \pm 0.29_{\text{sys}}$ kpc).

A very important result presented in publication **P1** was a comparison between the dereddened brightness I_0 of the bulge RR Lyrae stars and the red clump giants. It was evident that in the inner part of the bulge, narrowly in the area with $|l| < 3°$ and $|b| < 4°$, the RR Lyrae stars (the old population) trace the intermediate-age bar formed of red clump stars. In this area, the brightness of both type of stars increases with the increasing Galactic longitude. This is shown in Figure 1 taken from publication **P1**. Outside this area, the brightness of the RR Lyrae type stars seems to be constant at $I_0 \approx 15.0$ mag. This means that Population II is rather symmetric in galactic longitude in the outer bulge.

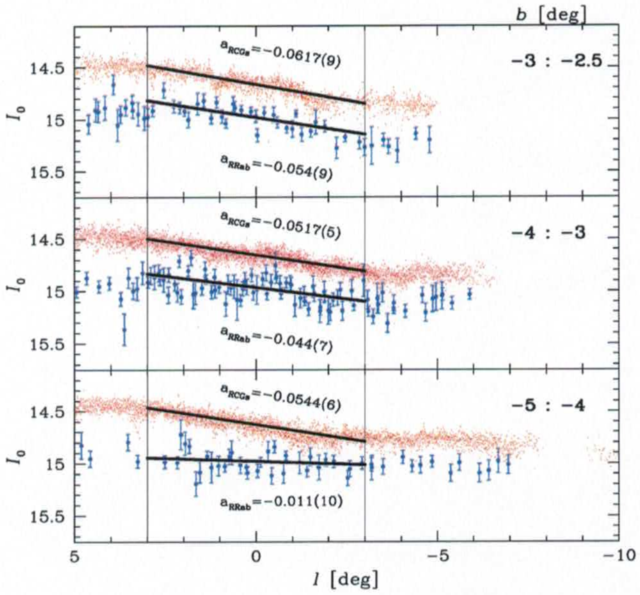

Figure 1. Dereddened *I*-band brightness distribution for bulge RRab stars (blue points) in comparison with red clump stars (red points) in three stripes along the Galactic plane (the latitude ranges are given in the upper right corners). In the inner bulge, the RR Lyrae stars clearly form a structure along the Galactic bar formed of red clump stars.

Publication **P1** is the most cited of all my papers. According to the SAO/NASA Astrophysics Data System (ADS) it has been cited 38 times by 16 February 2016. One year later the OGLE-III RRab variables were used by Dékány *et al.* (2013) for an independent verification of the distribution of these stars. The authors combined *I*-band observations from OGLE with K_s-band (2.2 μm) observations from the 4-m VISTA telescope used by the VVV survey. The advantage of near-infrared over optical observations (particularly in the *V* band) is that the period-luminosity relations gets narrower with the increasing wavelength and they are less metallicity dependent. Near-infrared wavebands are much less sensitive to interstellar reddening than optical ones. According to Dékány *et al.* (2013) the bulge RR

Lyrae stars do not trace a strong bar. Perhaps, in the very inner part the variables form a slightly elongated structure inclined at 12.5° to the Sun–GC line. New, larger samples of RR Lyrae stars from the Galactic bulge could show the truth.

Once the OGLE-IV bulge RR Lyrae collection has been completed, I started to analyze it. Results are published in publication **P2**. It was obvious for me that this time only RRab stars can be used to properly describe the geometry of the old bulge population. As it was mentioned earlier, the collection of the RRab variables was highly complete. The OGLE-IV collection contains 27258 such objects. Prior to the analysis, I had to clean the sample and set boarders of "complete" area. I assumed that toward this area all RRab variables had been detected. Few stars, that could have been missed during the searches, have no impact on the final results.

An important step forward in the analysis of the RR Lyrae stars from OGLE-IV was the work on interstellar extinction toward the bulge by Nataf *et al.* (2013). In their work the authors combined optical data from OGLE-III with near-infrared data from the 2MASS and VVV surveys for the bulge red clump stars. In paper **P2**, I use their relation on the extinction A_I and the map of reddening $E(J–K_s)$ prepared by Gonzalez *et al.* (2011) from the VVV data. This time I also rely on better determinations of the mean $V–I$ colors of the RR Lyrae stars thanks to much better V-band coverage in the fourth phase of OGLE in comparison to OGLE-III. The new approach has brought a better fit of the King (1962) profile for the old population and a value of the distance to the GC $R_0 = 8.27 \pm 0.01_{stat} \pm 0.40_{sys}$ kpc, being in excellent agreement with recent results from other measuring methods, for example with $R_0 = 8.34 \pm 0.16$ kpc from trigonometric measurements of masers in radio (Reid *et al.* 2014) and $R_0 = 8.27 \pm 0.09_{stat} \pm 0.1_{sys}$ kpc from the dynamics of the nuclear cluster stars (Chatzopoulos *et al.* 2015). The estimated small statistical error results from a large number of RRab stars, while the relatively large systematic error results mainly from the uncertainty of the absolute brightness of RR Lyrae, reaching 0.1 mag in V.

Having a much larger sample of RRab stars from OGLE-IV in comparison to OGLE-III, I could analyze the spatial shape of the old bulge population in more details. I did it in two steps. In the first step, I looked at the observed distribution in the sky. Then, in the second step I analyzed the distribution onto the plane of the Milky Way. It turned out that at distances 3°–8° from the Center the constant surface density lines in the sky are ellipses flattened along the Galactic equator with a flattening of about 0.33. This already implies that the old bulge is not spherically symmetric. The analysis of the distributions of RRab variables along selected sightlines within the Milky Way plane has shown that their maxima gets closer to us with the increasing Galactic longitude. This means that there must be an axis in the Galactic plane inclined to the Sun–GC line (Figure 2) and the old population has the shape of a triaxial ellipsoid. Constant density contours in the plane of the Galaxy, or in the polar view, are clearly elliptical. I found the inclination angle (of the major axis of the ellipsoid) to be 20° ± 3° and the axis ratio of 1:0.49:0.39, with an error of 2%. The obtained results clearly show that population II stars trace the intermediate-age bar in the inner part. It is very likely that old RR Lyrae stars feel gravitational forces from the more massive bar. I found that the spatial density profile of RRab stars can be described by a single power law with an index of -2.96 ± 0.03. Using the larger sample of stars from OGLE-IV I demonstrated that the RR Lyrae population is metal-uniform with a mild negative gradient from the Center. Another important result was to show that the distribution of these variables at latitudes higher than 5° is unimodal and symmetric. Namely, that old bulge stars do not form an X-shaped structure.

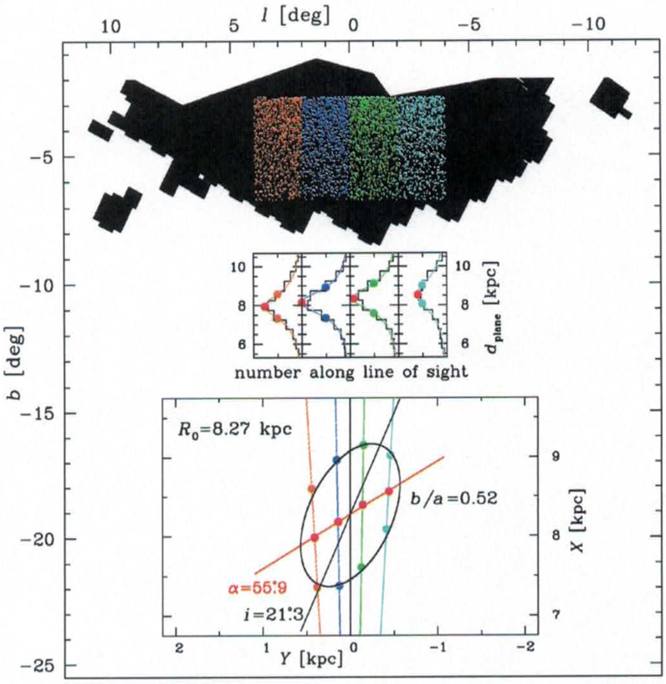

Figure 2. Results from the analysis of the number density distribution of bulge RRab stars along four selected directions, marked with four different colors. The stars were taken from the four rectangle areas shown in the map (in the upper part). The maxima of the distributions, marked with red dots, clearly get closer to us with the increasing Galactic longitude (middle inset, from right to left). In the projection onto the Galactic plane (lower inset), points of the same density level form an tilted ellipse.

Finally, the biggest surprise, and in my opinion the most excited result presented in **P2**, is the evidence for multiple old bulge populations. I have found that the RRab stars form two very close sequences in the period–amplitude (Bailey) diagram. This is even better seen for stars with a small scatter around the fit to the phased light curve, or Blazhko-free RR Lyrae stars (Figure 3). (The Blazhko effect is a long-period modulation of the pulsation period and amplitude.) The presence of two close sequences in the Bailey diagram means that we observe two populations with slightly different metallicities. The two populations may be of different age, but according to the current knowledge, the shift in the period in the Bailey diagram indicates rather a difference in the metal content. Due to the very small separation and a large scatter here, it is very difficult to assess the metallicity difference between the populations. A more quantitative analysis of the period–amplitude diagram has shown that about 12% of RR Lyrae stars belong to the less metal-poor population A and 48% of the stars to the more metal-poor population B. Most of the remaining stars seem to represent other, even more metal-poor populations. The presence of multiple, relatively abundant, old populations indicates that our Galaxy was formed through mergers in the early stages of evolution and not a single collapse of one cloud of gas. This is the first result supporting the hierarchical scenario from observations of the inner Milky Way regions. According to ADS from 16 February 2016, my publication **P2** has been cited 15 times.

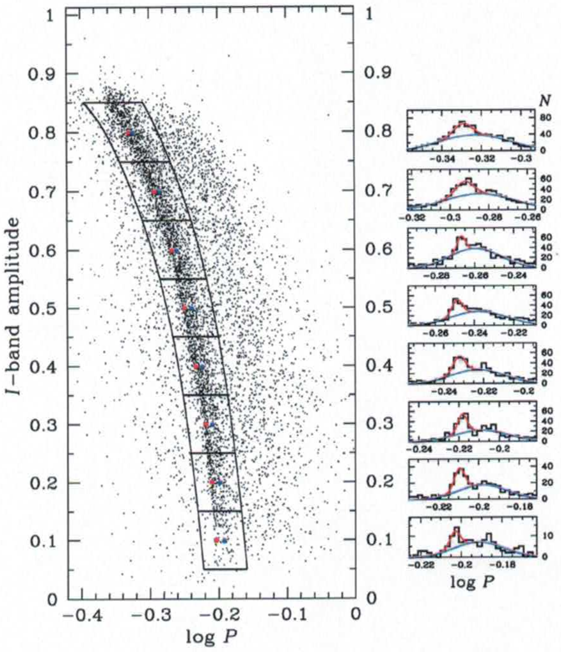

Figure 3. Period–amplitude diagram for the bulge RRab stars with a low scatter in their light curves. Stars form two very close sequences. Results of the fitting of a sum of two Gaussians to the histograms for eight amplitude ranges are shown on the right side.

My work in recent years concentrated not only on Galactic bulge objects. I have also searched for and analyzed pulsating stars in the Galactic disk. The huge stripe of the Milky Way has not been surveyed for variable objects fainter than V~13 mag yet. Brighter objects have been cataloged by GCVS (General Catalogue of Variable Stars, Samus *et al.* 2013) and ASAS (All Sky Automated Survey, Pojmański 2002). However, it is important to mention that these catalogs are certainly not complete. Deep OGLE-IV observations (down to I~19,5 mag) of the whole Galactic stripe visible from Las Campanas Observatory (about 2/3 of its total length) are underway. During the third phase of the project, conducted in years 2001–2009, OGLE observed 21 selected fields near the Galactic equator located about 52°–73° toward negative longitudes. It was a total area of 7,12 deg^2. Depending on the field, between 800 and 2700 I-band images were collected, with the best cadence of 15 min. The aim of the monitoring was to search for planetary transits. As a result five extrasolar planets were detected, for instance OGLE-TR-111 (Udalski *et al.* 2002). I searched the data for any kind of stellar variability. Due to irregular coverage in time and a very high probability of finding various transient objects (such as dwarf novae, Be type stars, T Tauri stars, and stars with flares), I decided to undertake a visual inspection of all variables with a strong variability signal (S/N > 10). About 345 000 detections were inspected. Almost one-fourth of this sample was independently inspected by undergraduate student Przemysław Mróz. I was his supervisor and the second author of his first publication on the discovery of forty new dwarf novae in the Galactic disk.

The investigated area of the sky was kind of *terra incognita*, since regions close to the Galactic plane are expected to be full of stars of different populations. Moreover, the observed direction is roughly tangent to the Scutum–Centaurus spiral arm. There are stars of different luminosity classes at unknown distances and with unknown reddening values. The classification of variable stars requires good knowledge on their various types and photometric properties. The final list of variable objects had to be cleaned from artifacts, or detections mimicking nearby real variables.

The searches for variable objects in the OGLE-III Galactic disk fields led to the discovery of

214 pulsating stars (publication **P3**), 11589 eclipsing binaries (Pietrukowicz *et al.* 2013), 40 dwarf novae (Mróz, Pietrukowicz *et al.* 2013), and 16000 not published variables of other types, mostly spotted stars. The variety of pulsating stars among over two hundred stars is large. Paper **P3** reports on the detection of 20 classical Cepheids (Figure 4), 45 RR Lyrae type stars (among them 36 RRab and 9 RRc), 31 long-period variables (18 Miras i 13 semi-regular stars), one pulsating white dwarf (probably of ZZ Ceti type), and 58 very likely delta Scuti type stars. All objects but one Cepheid are new discoveries. In additon, the paper reports on 6 candidate Type II Cepheids and 60 short-period (< 0,23 d) multi-mode pulsating objects. The presence of short periods and low amplitudes (of a few hundredths mag) indicates only two possible solutions in the realm of pulsating stars: either of beta Cephei type (hot and massive stars of spectral types O9–B5 and luminosity classes I–V) or delta Scuti type (intermediate-mass stars, slightly hotter than the Sun, of spectral types A0–F9 and luminosity classes III–V). Due to the lack of information on reddening and distance to the stars, it is impossible to distinguish between the two variability types based on the *VI* photometry only. To unambiguously classify these and other variables from OGLE I decided to conduct especially dedicated spectroscopic follow-up observations, described later. Among the 58 likely delta Scuti type stars, the lack of confidence referred to object OGLE-GD-DSCT-0058. This star varies with an exceptionally high amplitude (0,24 mag in *I*) at an extremely short period (0,0196 d). The remaining 57 variables are *bona fide* high-amplitude delta Scuti type stars (HADS) pulsating in one or more modes. In the analysis of multi-mode stars, Petersen diagram is a very useful tool. In this diagram diagram, in which the shorter-to-longer period ratio is shown as a function of the longer period, stars pulsating in radial modes form roughly horizontal sequences.

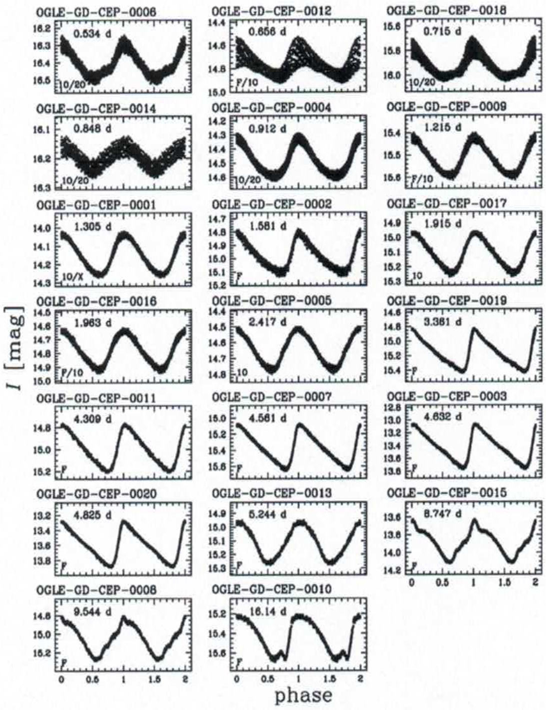

Figure 4. Phased *I*-band light curves for 20 detected classical Cepheids in the OGLE-III Galactic disk fields. Identification names of the variables and their periods are given.

In six of the discovered delta Scuti type stars I detected three radial modes and in one more star even four modes. These stars may pulsate in other, higher modes, but their detection requires a longer monitoring or rather more accurate observations from space (like in the case of Kepler, CoRoT, MOST missions and the BRITE constellation). For the seven multi-mode radially pulsating delta Scuti stars from OGLE-III, only based on the information on periodicities, it was possible to theoretically determine their physical parameters, such as mass, metallicity, age, and surface temperature. An additional information on the observed brightness allowed determination of the distance and reddening. Five of the variables turned out to be relatively young objects, 0.5–1.5 billion years old, on the main sequence. The remaining two variables are metal poor and much older, of 4–6 billion years. The derived distances to the seven stars are between 2.5 and 6.2 kpc.

These results show a great potential of multi-mode radially pulsating delta Scuti type variables in the application to the Milky Way structure studies and asteroseismology. In our Galaxy, there must be thousands of such pulsators, representing different populations. In near future, it will be possible to compare distance measurements from asteroseismology with measurements from the astrometric Gaia mission. It will be a good test for the pulsation theory and the theory of stellar interiors.

Among pulsating stars, the largest applications to the knowledge on the structure and formation history of the Galactic disk and halo have classical Cepheids (population I stars) and RR Lyrae type stars (population II). Both are bright standard candles seen from distances of kiloparsecs, even behind thick dust clouds. Classical Cepheids are known from the period–luminosity relation (Leavitt 1908). The more massive star is, the more luminous is and pulsates with a longer period. Classical Cepheids obey a period–age relation (Bono *et al.* 2005). They would allow to trace the current spiral structure and to follow the recent star formation history in the thin disk (dating back up to 1 Gyr). A large set of classical Cepheids should help in answering the following important questions related to the Galactic disk, such as: the true number of spiral arms, the pitch angle of the spiral structure, the speed of the spiral pattern, and the star formation rate. Recently, some attempts have been made (*e.g.* Mel'nik *et al.* 2015), but the picture drawn from a sample of known Cepheids with estimated distance is not very clear yet. The stars seem to concentrate only along the nearby Sagittarius arm. In paper **P3**, I present the most completed list of known Galactic classical Cepheids, which will be used in future studies. I supplemented the list of known objects from GCVS with about two hundred stars from the ASAS survey and other sources including OGLE-III. From time to time I update the list for new discoveries. Currently, as for 16 February 2016, it contains information on 883 variables. The list is available to the astronomical community at the following Internet address: ftp://ftp.astrouw.edu.pl/ogle/ogle3/OIII-CVS/gd/cep/GalCep.list. Other nearby directories there contain detailed information on other variable objects detected in the OGLE-III Galactic disk fields and other OGLE fields.

The searches for pulsating variables in the deep images from OGLE-III, presented in publication **P3**, was kind of a test of how many of such variables are expected to be found in the shallow OGLE-IV Galaxy Variability Survey, currently conducted from Las Campanas Observatory. The searches for classical Cepheids in the 7.12 deg^2 OGLE-III Galactic disk area led to the detection of 20 such pulsators. All of them are brighter than 16.5 mag in *I*. Nine other classical Cepheids had already been known in this area, but all of them are saturated in the OGLE-III images. If we scale the small numbers to the whole observed disk, we would expect the presence of about 3000 classical Cepheids. The truth is that we do not know how many of them is hidden behind the clouds of dust.

One may think that in the small sample of 214 various pulsating variable stars detected in the tiny area of 7.12 deg^2 of the Galactic disk there is no valuable information on the Milky Way structure. But it turned out that the metallicity distribution for 36 RRab stars has two maxima, one at about –1.3 dex and the second one at –0.4 dex. The boundary value is at –0.7 dex on the Jurcsik (1995) metallicity scale. It gives –0.95 dex on the Zinn & West (1984) scale. This is very close to –1.0 dex, which is considered to be the metallicity limit between halo and think disk stars (*e.g.* Ivezić *et al.* 2008). A much larger sample of RR Lyrae variables from the disk regions would help to obtain a better metallicity distribution and to better describe the properties of the two Galactic components. According to ADS, publication **P3** has been cited 10 times by 16 February 2016.

Searching for variable stars in the OGLE-III disk fields led to the discovery of thousands of new objects, including over two hundred pulsating stars. Many of them have been classified, but in some cases an unambiguous classification was not possible based on the *VI* photometry only. Due to unknown reddening and distances to the objects it was impossible to distinguish between the beta Cephei and delta Scuti types. *UBV* observations and the construction of a color-color (*U–B vs. B–V*) diagram would probably indicate the real type. My concerns also referred to objects OGLE-GD-DSCT-0058 and OGLE-GD-CEP-0013, and other variable stars with non-standard light curves. I decided to conduct a dedicated low-resolution spectroscopic observations to obtain a confident classification. In October 2013, together with my collaborators from Chile, I applied for observing time on the 2.5-m du Pont telescope located next to the OGLE telescope in Las Campanas Observatory. In December 2013 I was awarded two nights at the end of April 2014. The weather was very good and I collected spectra for over 30 stars. Several weeks later I reduced the data and made spectral classification of the observed objects. Results are presented in publication **P4** and example spectra are shown here in Figure 5. My investigation has shown that 12 (out of 60 reported in paper **P3**) unclassified short-period multi-mode objects have spectra dominated by hydrogen lines, as it is observed in stars of the spectral type A. Hence, all of the variables are of delta Scuti type. Another variable, OGLE-MUS101.3.34906, showing a strange wavy light curve, also was found to be of this type. I hoped to find beta Cephei stars in the OGLE-III disk fields, but it turned out to be difficult. On the other hand, my studies have shown that delta Scuti type variables are numerous in the Galactic disk and await discovery.

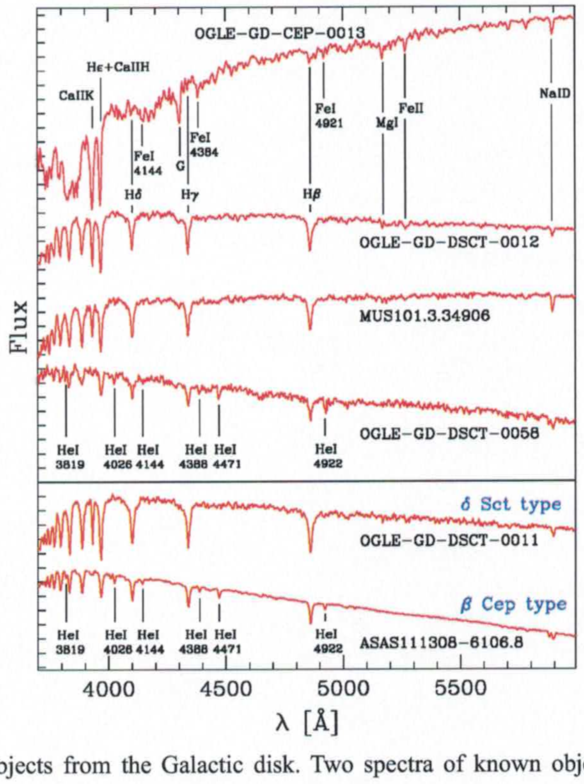

Figure 5. Spectra of selected objects from the Galactic disk. Two spectra of known objects in the bottom served for a comparison.

I have confirmed that star OGLE-GD-CEP-0013 with a peculiar light curve is a classical Cepheid. Its spectrum is close to a G0 type star rich in iron. Spectrum of object OGLE-GD-DSCT-0058 is characterized by a strong continuum rising to the blue. Superimposed hydrogen and neutral helium lines indicate a high temperature of this object. Fitting model atmospheres brought the following parameters: effective temperature $T_{\rm eff} \approx 33000$ K (corresponding to spectral type O9) and surface gravity log $g \approx 5.3$ (in the units of cm/s²). This means that it cannot be a delta Scuti type star. In 2016 I conduct follow-up studies of this star. I have been awarded observing time to collect *UBVI* photometry for this object on the 1.0-m Swope telescope and to take spectra of other similar objects with the 8.2-m Gemini South. New observations should help to answer the question on the real nature of OGLE-GD-DSCT-0058.

In coming years, I plan to continue studies on the structure and evolution of our Galaxy. Searching for classical Cepheids is one of the prime goals of the OGLE-IV Galaxy Variability Survey of the Milky Way disk available from Las Campanas Observatory. This is a very time-consuming task, since the survey covers an area of about 1400 deg^2 along the Galactic equator.

5. Presentation of the remaining scientific achievements.

I was born on 23 November 1978 in Gorzów Wielkopolski, Poland. My interest in astronomy grew up with me. I had to broad this passion on my own, since in the city of over 120 000 inhabitants I did not know anyone interested in skygazing. The closest location of the Polish Society of Astronomy Amateurs still can be found about 100 km away. I participated in the Polish Astronomical Seminar for High-School Students and twice qualified for the national finals in Grudziądz. I also participated in the Polish Astronomical Olympiad, qualifying for the final in 1996 and winning the fifth place and the laureate title in 1997. I quickly decided to study astronomy at Warsaw University. I entered the university in 1997 and obtained the MSc degree in 2002.

My research area is observational stellar astrophysics. I have searched for and analyzed variable stars of different types (pulsating stars, eclipsing binary stars, cataclysmic systems). I have studied star clusters (open clusters as well as globular clusters) and recently Galactic structure based on photometric data collected by the OGLE team, of which I am a member. I wrote my first scientific articles when I was an undergraduate student. A series of three single-author publications (Pietrukowicz 2001, 2002, 2003) were devoted to secular period changes in known classical Cepheids from the Magellanic Clouds and our Galaxy. Prof. Bohdan Paczyński invited me to Princeton University for a month in summer 2001 and helped me in writing my first publication. The papers show that evolutionary models of long-period Cepheids (>10 d) predict period change rates much higher than they are observed. According to the ADS database my first three publications have been cited 33 times by 16 February 2016. In my master thesis, I searched for variable stars in archival images of the central part of the globular cluster M22 from the Hubble Space Telescope. I discovered 11 new variables, including one object of still unknown nature (Pietrukowicz & Kaluzny 2003). I obtained my PhD degree at Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences in Warsaw in March 2007, under the supervison of Prof. Janusz Kałużny. He was the principal investigator of the Cluster AgeS Experiment (CASE), a long-term photometric survey of nearby Galactic globular clusters with the aim to improve distance and age estimations to these objects. In my PhD thesis, I searched for cataclysmic systems erupting as dwarf novae in selected globular clusters from the CASE survey. By using, at that time very modern, image subtraction method I found two new dwarf novae (one in the globular cluster M22 and another one in M55) and increased the total number of known such objects in globular clusters from nine to eleven. I showed that these objects are rare (Pietrukowicz *et al.* 2008). It is very likely that properties of cataclysmic systems in clusters are different in comparison to systems located in scarce Galactic field. One of the hypothesis says that white dwarf primaries in cataclysmic systems in clusters rotate faster due to high spatial density of stars. Such fast rotators have stronger magnetic fields which trim or even prevent formation of the accretion disks. According to other hypothesis mass transfer rates from the secondaries in cluster systems are lower than in field systems and therefore outbursts are less frequent. During the searches for erupting objects in the CASE clusters, serendipitously I detected a main belt asteroid moving in the foreground of the globular cluster M22. It turned out to be an object discovered several years earlier and designated (35690) 1999 CT21, for which now it was possible to improve orbit parameters and determine the rotation period (Pietrukowicz *et al.* 2006). Nevertheless, the biggest surprise was the discovery of a microlensing event in the field of M22 that happened in 2000 (Pietrukowicz *et al.* 2005). Observations using adaptive optics, which I obtained with the ESO Very Large Telescope (VLT) eleven years after the event, showed the lens separated from the source in the direction and speed exactly in agreement with the relative proper motion of M22 against three times more distant Galactic bulge stars (Pietrukowicz *et al.* 2012). This is the only one microlensing event confirmed to be caused by a globular cluster star to date.

I would like to write here that during my PhD studies I worked on a difficult observing task, unsolved due to technical reasons by anyone so far. I was searching for quasars behind the Galactic bulge. They would serve as astrometric reference points in studies on the dynamics of the bulge. Due to large amount of interstellar dust in the Milky Way disk distant stars and extragalactic sources are much fainter and very often severely reddened. This is difficult even in the direction of Baade's Window, a region toward the bulge with a relatively low extinction. I searched for quasars by reducing spectra of over 1500 objects during my summer stay at ESO Headquarters in 2005. The spectra were obtained by Dr. Adam Dobrzycki with VLT for objects selected based on the OGLE-II photometry. One year later I verified candidates for quasars immediately after taking spectra by myself on the ESO 3.6-m telescope on La Silla in Chile. Those were my first observations collected with a large world-class instrument. Unfortunately, the weather was rather poor and the result negative again.

In years 2007–2009 I was a postdoc in Departamento de Astronomía y Astrofísia Pontificia Universidad Católica in Santiago de Chile. I was hired to help in the start of the ESO public survey called *VISTA Variables in the Via Lactea* (VVV, Minniti, … , Pietrukowicz *et al.* 2010). The survey was conducted on the 4-m VISTA telescope next to Cerro Paranal in Chile in years 2010–2015. It was a near-infrared survey of nearly the whole Galactic bulge and an adjacent part of the Galactic disk. My collaborators were Prof. Dante Minniti (PI of VVV) and Prof. Marcio Catelan. While waiting for the launch of the VVV project I analized archival ESO data (for instance, I searched for planetary transits, Pietrukowicz *et al.* 2010) and several times applied for observing time and collected data for Galactic field objects as well as globular clusters. At the time of my abroad position I gathered a lot of observational experience with different instruments attached to many world-class telescopes. Part of the observations were taken on ESO telescopes in service mode. This required perfect preparation of observing blocks.

My observational experiences by the end of 2015 are the following. I have spent a total of 306 nights at 1–2-m class telescopes (including 230 nights on the 1.3-m OGLE telescope), 5 nights at 4-m telescopes, and 4 nights at 6.5-m Magellan telescopes, all located in the Chilean Atacama Desert. About 38 hours of my observations have been collected in service mode, almost half of them on the 8.2-m ESO VLT units. In total, I have collected observational data with 13 various telescopes, using 16 different instruments. Among them were single and multi-object spectrographs as well as imaging cameras used in the optical and near-infrared regime, including the adaptive optics.

During my postdoc position in Chile I met many astronomers, not only from local astronomical institutions, but also visiting observers from around the world. For one year I was in charge of the department seminars. My observing runs in Las Campanas Observatory for the OGLE project in recent years also allow me to keep in contact with known astronomers and to meet new people, particularly from Chile and USA.

Nevertheless, the best opportunities to promote new results and discoveries are scientific conferences. By the end of 2015 I have participated in 14 international conferences, during nine of which I gave talks and during four meetings I presented posters with my results. I have participated in the General Assembly of the International Astronomical Union twice. During the last assembly in Honolulu, USA, in August 2015, I had a talk and a poster on separate topics. At the end of 2015 I was invited, for the first time, to give a talk on an international conference devoted to cosmic distance scales, organized in Beijing in May 2016. In recent years, I have given several talks in Polish astronomical institutions and also during one of the assembly of the Polish Astronomical Society.

In October 2010 I began my postdoctoral position at Warsaw University Observatory. I was funded from the European Research Council (ERC) Advanced Grant awarded to Prof. Andrzej Udalski for years 2010–2014. Since 2015 I am funded from MAESTRO grant of the Polish National Science Centre (NCN) to Prof. Udalski. The aim of the grants is a financial support of the long-term OGLE project lead by Prof. Udalski. I am an active member of the team. I observe regularly, reduce and analyze photometric data, and discuss other topics undertaken by other team members. OGLE data have huge application to many areas of stellar astrophysics, extragalactic studies, and also Solar System studies. OGLE publications, of which I am a co-author, refer to different topics, such as: studies of variable stars of various types, searches for microlensing events, searches for microlensing planets, searches for supernovae behind the Magellanic Clouds and other transients (like classical novae and dwarf novae), photometric monitoring of Active Galactic Nuclei, studies of the structure and populations in the Magellanic System, astrometry, searches for Kuiper Belt Objects and improvement of their orbits. From time to time I conduct follow-up observations (both photometric and spectroscopic) using other astronomical facilities. I am an author of 109 scientific articles published in astronomical peer-reviewed journals, in 21 of which I am the first author. According to the ADS database, by 16 February 2016 my publications have been cited 1423 times and my Hirsch index is 19.

Paweł Pietrukowicz

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