Research summary

Anna Marciniak

Astronomical Observatory Institute
Adam Mickiewicz University
in Poznań

Poznań, 2019

1 Name

Anna Marciniak

2 Education

17.04.2009	PhD degree, Adam Mickiewicz University in Poznań; distinguished thesis (written in Polish): "Modelling asteroid physical properties with lightcurve inversion method" supervisor: Prof. dr hab. Tadeusz Michałowski
03.06.2003	Master's degree, Adam Mickiewicz University in Poznań; thesis: "Determining asteroids sidereal period and sense of rotation with epoch method" supervisor: Prof. dr hab. Tadeusz Michałowski
12.1999	*Certificate in Advanced English* from University of Cambridge, Local Examination Syndicate

3 Employment

since 10.2009	Post doctoral position in Astronomical Observatory Institute, Adam Mickiewicz University in Poznań
05.2008 – 06.2009	Translator of popular science movies in: „Iglo Studio" and „Rino Media Force, Studio nagrań lektorskich On-Line"

4 Habilitation research accomplishment

4.1 title

Diminishing the influence of selection effects on known physical properties of asteroids

4.2 Publications

H1 **Marciniak A.**, Bartczak P., Santana-Ros T., Michałowski T., Antonini P., Behrend R., Bembrick C., Bernasconi L., Borczyk W., Colas F., Coloma J., Crippa R., Esseiva N., Fagas M., Fauvaud M., Fauvaud S., Ferreira D. D. M., Hein Bertelsen R. P., Higgins D., Hirsch R. Kajava J. J. E., Kamiński K., Kryszczyńska A., Kwiatkowski T., Manzini F., Michałowski, J., Michałowski M. J., Paschke A., Polińska M., Poncy R., Roy R., Santacana G., Sobkowiak K., Stasik M., Starczewski S., Velichko F., Wucher H., Zafar T. **2012**
„Photometry and models of selected main belt asteroids XI. Introducing ISAM - Interactive Service for Asteroid Models"
Astronomy & Astrophysics 545, A131, 31 pp.
Number of citations: 13, IF(2012)=5.084
My participation in this publication consisted in choosing the targets for complementary observations, planning and performing them, and reducing large part of new data (~60% of data from the years 2004–2011). I also created the

models of all the targets and wrote whole text of the manuscript, and substantively supported the ISAM service development. My estimated participation is 80%.

H2 **Marciniak A.**, Pilcher F., Oszkiewicz D., Santana-Ros T., Urakawa S., Fauvaud S., Kankiewicz P., Tychoniec Ł., Fauvaud M., Hirsch R., Horbowicz J., Kamiński K., Konstanciak I., Kosturkiewicz E., Murawiecka M., Nadolny J., Nishiyama K., Okumura S., Polińska M., Richard F., Sakamoto T., Sobkowiak K., Stachowski G., Trela P. **2015**
„Against the biases in spins and shapes of asteroids"
Planetary and Space Science, 118, 256-266
Number of citations: 9, IF(2015)=1.942
My participation in this publication was that I organised the observing campaign of previously omitted asteroids, engaging observers from 8 stations in 5 countries. I also performed and reduced part of the observations and analysed the rotation periods of all studied asteroids. I wrote the whole text of the manuscript. My estimated participation is 80%.

H3 **Marciniak A.**, Bartczak P., Müller T., Sanabria J. J., Alí-Lagoa V., Antonini P., Behrend R., Bernasconi L., Bronikowska M., Butkiewicz-Bąk M., Cikota A., Crippa R., Ditteon R., Dudziński G., Duffard R., Dziadura K., Fauvaud S., Geier S., Hirsch R., Horbowicz J., Hren M., Jerosimic L., Kamiński K., Kankiewicz P., Konstanciak I., Korlevic P., Kosturkiewicz E., Kudak V., Manzini F., Morales N., Murawiecka M., Ogłoza W., Oszkiewicz D., Pilcher F., Polakis T., Poncy R., Santana-Ros T., Siwak M., Skiff B., Sobkowiak K., Stoss R., Żejmo M., Żukowski K. **2018**
„Photometric survey, modelling, and scaling of long-period and low-amplitude asteroids"
Astronomy & Astrophysics, 610, A7, 33 pp.
Number of citations: 4, IF(2017)=5.565 *My participation in this publication was to introduce the idea of simultaneous asteroid modelling with two different inversion methods in order to verify them, and to scale the resulting models in thermophysical modelling and by stellar occultations independently. I also planned and coordinated a large observing campaign, performed and reduced part of the observations, created the convex inversion models of all the studied targets, interpreted the results and wrote 90% of the manuscript. My estimated participation is 70%.*

H4 **Marciniak A.**, Alí-Lagoa V., Müller T. G., Szakáts R., Molnár L., Pál A., Podlewska - Gaca E., Parley N., Antonini P., Barbotin E., Behrend R., Bernasconi L., Butkiewicz - Bąk M., Crippa R., Duffard R., Ditteon R., Feuerbach M., Fauvaud S., Garlitz J., Geier S., Goncalves R., Grice J., Grześkowiak I., Hirsch R., Horbowicz J., Kamiński K., Kamińska M. K., Kim D.-H., Kim M.-J., Konstanciak I., Kudak V., Kulczak P., Maestre J. L., Manzini F., Marks S., Monteiro F., Ogłoza W., Oszkiewicz D., Pilcher F., Perig V., Polakis T., Polińska M., Roy R., Sanabria J. J., Santana-Ros T., Skiff B., Skrzypek J., Sobkowiak K., Sonbas E., Thizy O., Trela P., Urakawa S., Żejmo M., Żukowski K.
„Thermal properties of slowly rotating asteroids. Results from targeted survey" Astronomy & Astrophysics, accepted for publication

DOI: 10.1051/0004-6361/201935129
Number of citations: 0, IF(2017)=5.565

My participation in this publication was to plan and coordinate the observing campaign in 20 stations from 12 countries and with Kepler Space Telescope. I also performed and reduced part of the observations, created the models of all studied asteroids, interpreted the results, and wrote 75% of the manuscript. My estimated participation is 70%.

4.3 Description of the scientific goals and achieved results

4.3.1 Introduction

Studies of asteroid physical properties like: rotation frequency, spin axis orientation in space, three-dimensional shape, size, albedo or thermal inertia of the surface matter are of key importance in the context of the formation and evolution of the solar system, and Earth-like rocky planets and satellites in particular. The oldest asteroids are considered the original leftover planetesimals from various stages of accretion in protoplanetary disk. In gaines particular importance in the context of discoveries of asteroid belts in extrasolar planetary systems, where planets are apparently created similarly as they were in our solar system (Moerchen et al. 2007; Lawler et al. 2009).

After the stage of planets creation, and as a result of migration of giant planets (so called Grand Tack, Walsh et al. 2011), heavy bombardment epoch started, and it resulted in large mixing in the main belt area and in other minor bodies reservoirs. It was then when larger bodies have been catastrophically disrupted into whole groups of smaller remnants – so called asteroid families – sharing similar dynamical and physical properties. Their further fate was governed by gravity, but also by thermal effects from heating and non-symmetric reradiation of thermal energy. These effects are capable of effectively shifting smaller bodies (up to 30–40 km in diameter, Vokrouhlický et al. 2015) into the zones of major resonances, where they can migrate in the near Earth area, becoming Near Earth Asteroids (NEAs). Thermal effects can also influence the spin state of small bodies, spinning them up or down, but also changing the inclination of their spin axes. The first of the effects, influencing orbital motion of minor bodies is called the Yarkovsky effect, and the other: YORP effect (an acronym from the names of its researchers: Yarkovsky, O'Keefe, Radzievskii, and Paddack). Both effects strongly depend on the spin state and physical properties of the asteroid surface, e.g. on thermal inertia.

In my research I work on determining rotation periods of main belt asteroids, and on reconstructing their spin axis positions with 3D shapes, basing on multi-apparition photometric data and the lightcurve inversion method. Then, I put to scale those scale-free asteroid models from lightcurve inversion, using data obtained in the infrared range and also using stellar occultatins by asteroids. I especially focus on targets omitted by previous surveys, motivated by huge observing selection effects existing in this area. Obtained asteroid models are then used e.g. in collective studies on statistics of spatial spin axis distributions, or on rotation frequencies versus sizes, that in turn are essential basis for dynamical studies of collisional history of asteroids (Durda et al. 2007), or for research on formation ages and evolution of asteroid families under the Yarkovsky drift (Vokrouhlický et al. 2006).

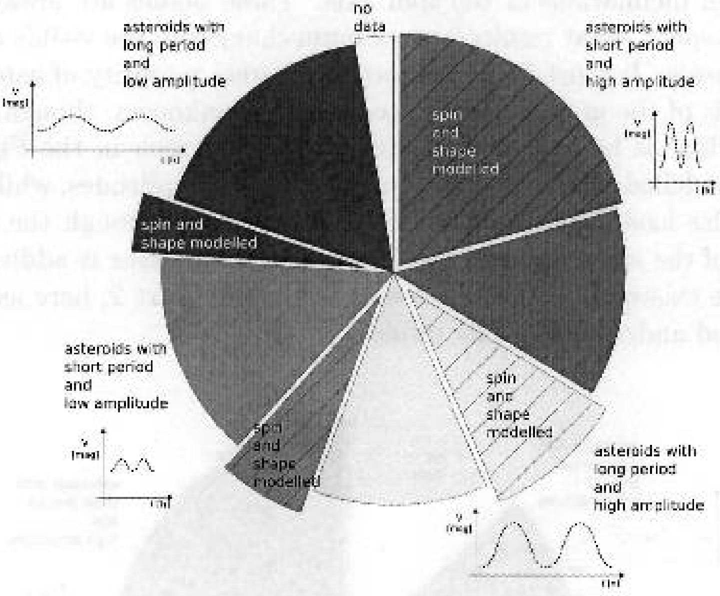

Figure 1: Current distribution of known periods and maximum amplitudes among the ~1200 brightest main belt asteroids (based on LCDB by Warner et al. 2009, updated 5 September 2016). Boundary absolute magnitude is H=11 mag, and division values are P=12 hours and a_{max}=0.25 mag. The amount of spin and shape modelled targets is marked within each group. Asteroids with specific features are over-represented, while others are largely omitted. (Marciniak et al. 2018 – H3)

On the basis of currently available sample of modelled asteroids one can get an impression that asteroids in great majority rotate fast, are strongly elongated in shape, and their spin axes avoid proximity of the ecliptic plane. However, when I did statistical survey of the sample of 1200 brightest asteroids, a group where almost all the targets have determined rotation periods and lightcurve amplitudes, it occurred that almost half of these targets rotate with periods longer that 12 hours (Fig. 1). It is much slower than widely believed: in the year 2002, when a set of review papers "Asteroids III" was issued, an average rotation period of large (~ 200 km in diameter) main belt asteroids was 8 hours, being 13 hours for the medium (D ~ 100 km), and 6 hours for the small asteroids(D ~ 10 km, Pravec et al. 2002). However slow rotators, with periods above 24 hours were excluded from this study.

Additionally, similarly large part of well-studied asteroid population displays small lightcurve amplitudes, not exceeding 0.25 magnitude, what makes them elusive for mass surveys aiming at asteroid modelling. Brightness variations of such targets are lost in the observing noise of majority of currently available photometric sky surveys, which average precision is around 0.1–0.2 magnitude (Hanuš et al. 2011). Thus almost half of the population is missing from the sample with available pole (that is coordinates of the spin axis position) and shape model. Moreover, it is widely believed that asteroid spin axes strongly avoid the surroundings of the ecliptic plane, orienting perpendicularly to it, what can be well explained as the outcome of the YORP effect (Vokrouhlický et al. 2003). However, it is certain that the spin axis distribution is strongly influenced by selection effects, favouring asteroids that always display substantial brightness variations – that is exactly those with high inclinations of the spin axis. These bodies are always viewed in an equatorial aspect, what results in maximum changes of the visible cross-section with their rotation. It must be noted here, that great majority of asteroids rotate around the axis of the greatest inertia tensor. It is unknown, though, how strong the observing bias is here, but its existence is clearly seen in the Fig. 2. There are very few modelled asteroids with small lightcurve amplitudes, while those with large amplitudes have been modelled in hundreds, even though the size of their population is of the same order as the former ones. The issue is additionally complicated by the existence of the white spot in the pie chart 2, here asteroids with unknown period and/or amplitude reside.

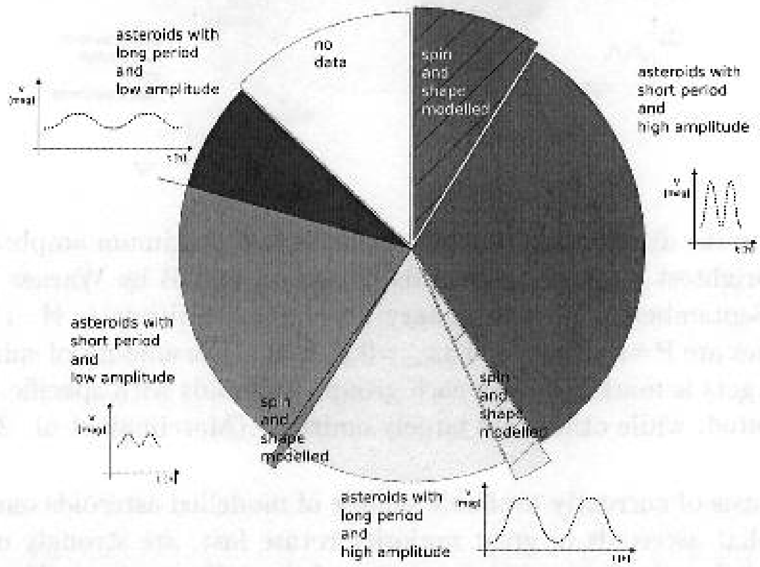

Figure 2: Same as Fig. 1, but for the ~2270 fainter main belt targets, with H between 11 and 13 mag (source: LCDB). There are a few hundres of large-amplitude targets (from those on the right side of the chart) with available spin and shape model, while only a few low-amplitude targets with a model (left side). Judging from the sample of only those small asteroids that have available shape models, and not taking into consideration the distribution of the amplitudes of all asteroids, can create a false impression that almost all small asteroids are strongly elongated. (Marciniak et al. 2018 – H3)

Above-mentioned observing selection effects are not easy to decrease, because such difficult targets require a few years worth of complete lightcurves, which means hundreds of hours of observations, and/or gathering very precise photometric data. In contrast, favoured targets are relatively easy to be modelled on the basis of available sparse data from sky surveys (such as Lowell Observatory database, Hanuš et al. 2011, Ďurech et al. 2016), where data on asteroid brightness variations are in the form of a few hundred datapoints spread over a few years, which means one datapoint or less per day. Some sort of a compromise is modelling asteroids on mixed data (using sparse-in-time data together with dense lightcurves from at least one apparition, Hanuš et al. 2013, 2016). Such an approach is also limited by the availability of the latter, favouring targets with large amplitudes and short periods.

Reconstructed asteroid shapes and rotation states are next utilised in further research, e.g. are an essential basis for thermophysical modelling. Recently I broadened by research interests by studies on asteroids in the infrared range of the electromagnetic spectrum. It turns out that having a precise spin and shape model of an asteroid, and a range of infrared data it is possible to determine its size, albedo and thermal inertia. Moreover, it is possible to predict its infrared flux far into the future, creating perfect calibration sources for all infrared observatories, both ground-based (eg. APEX, ALMA, or IRAM), and space (Herschel, WISE, or Spitzer). These facilities provide data on targets far exceeding our solar system: from quite nearby, like brown dwarfs or protoplanetary disks, to the furthest reaches of the Universe, like very young galaxies. It appears that for calibrating these instruments the planets are too bright, while even the brightest stars are too faint (Müller and Lagerros 2002), which is shown in Fig. 3. Particularly useful here are bright asteroids with small and slow brightness variations. It is an example of practical utilisation of asteroid models.

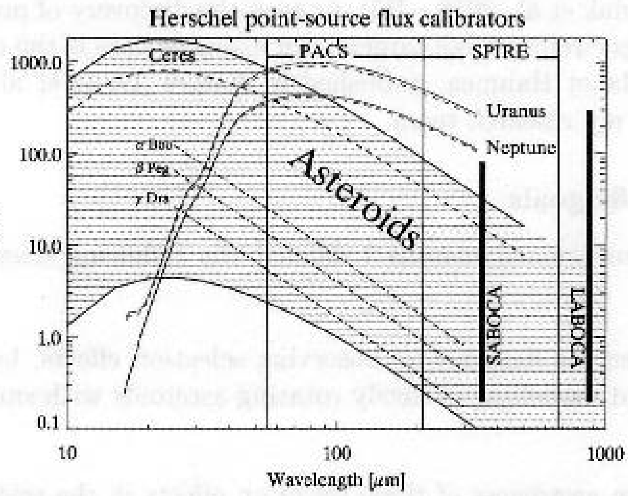

Figure 3: Spectral energy distribution for the brightest stellar calibration sources in the mid-infrared, for Uranus and Neptune (used for calibration in the millimetre and submillimetre wavelenghts), and for bright asteroid (shaded area). Working range of various Hershel and APEX instruments is shown. Asteroids bridge the gap between stellar and planetary calibrators, between mid-infrared and millimetre waves, and also between space- and groundbased infrared facilities (Müller and Lagerros 2002).

In the scientific aspect, it has been reported that e.g. asteroid thermal inertia grows with rotation period, as due to longer heating of given surface areas the heat wave penetrates deeper into the sub-surface (Harris and Drube 2016), probing layers of greater density. As a consequence, it seems that material properties (thermal conductivity, density and heat capacity) of various regolith layers covering asteroids could be determined this way, without the need to send there costly space probes. However so far, detailed models of slowly rotating asteroids were largely missing, disabling precise thermophysical modelling of such targets (see the red symbols in Fig. 6).

Another vital aspect of studying physical properties of asteroids is their size determination. Asteroid sizes known today are often only estimates based on comparing their visible and infrared fluxes, in the absence of the model; that is without the knowledge of spin axis orientation and the body shape; or are based on visible light only and an assumed albedo, where the uncertainty of the size determined this way reaches the factor of two. A precise way to determine sizes of these bodies, except for the above mentioned thermophysical modelling, is also the timing of stellar occultations by asteroids (example in Fig. 4). This relatively simple technique – it is sufficient to register the moment of disappearance and reappearance of the occulted star – is a powerful tool, especially when data for one event observed from various sites in the shadow path are available. Even though only a temporary, 2-dimensional cross section of the occulting body is obtained this way, with available full spin and 3D shape model from lightcurve inversion, it is possible to phase the model in, and scale it to the occultation chords. It allows for determining precise dimensions of this body, sometimes also confirming some shape features of the modelled shapes (see Fig. 19 in H3). Additionally, such fitting often enables the rejection of one of two possible pole solutions (Ďurech et al. 2011, Marciniak et al. 2018 – H3), or even the discovery of previously unknown satellites or rings circling these targets. An example here is the discovery of a ring around dwarf planet Haumea, published in *Nature* (Ortiz et al. 2017), with the participation of my research team.

4.3.2 Scientific goals

For the above mentioned reasons I defined the following scientific goals of my research:

1. To decrease the detrimental observing selection effects, by means of observations and modelling of slowly rotating asteroids with small lightcurve amplitudes.
2. To increase awareness of these selection effects in the scientific community, and focus the attention of observers on previously omitted targets.
3. To determine sizes of studied asteroids basing on thermophysical modelling and/or stellar occultations.
4. To create reliable calibration sources in the infrared range.
5. To verify if asteroid thermal inertia is indeed the larger the slower they rotate.

4.3.3 The first sample of asteroid models free from observing selection effects, and the tool for orienting the models

I first noticed the problem of observing selection effects, influencing the available sample of asteroids with known physical parameters, back in the year 2012. In the paper H1 I presented the models for possibly most varied sample of asteroids: with both short and long rotation periods (3 – 12 hours), with large and small lightcurve amplitudes (0.07 – 0.60 mag), and high and low spin axis inclinations to the ecliptic ($|\beta_p|$ from 88 to 10 degrees). Our sample also contained both large targets, with diameters of the order of 200 km, and small ones, only 13-km in size. The sample of these eight targets substantially increased the sample of lightcurve inversion modelled asteroids of that time. However, a substantial part of available models was already then based on sparse data (data in a form of single points per day), and as a consequence the shape models were only a coarse approximation of asteroid shapes. Asteroid shape models that I create are based exclusively on rich datasets of precise, dense lightcurves. Thus these models are usually more detailed and better approximate real shapes of asteroids. In contrast to them, models based exclusively or partially on sparse data usually have angular shapes, low resolution and tend to cause problems in further applications, like e.g. thermophysical modelling. Moreover, the uncertainty of determined spin axis position in models based on dense data is of the order of single degrees, while in those on sparse data it often reaches 20-30 degrees (Hanuš et al. 2016). Summing up, my research focus rather on quality than on quantity of the models.

In the paper H1 for the first time we put my newly created models to scale using stellar occultations by asteroids. Basing on the procedure described by Ďurech et al. (2011) we created our own tool for fitting 3D asteroid models to 2D sets of chords from occultation timings of stellar occultations by those minor bodies. In the meantime there appeared a neccessity to orient asteroid models in the sky plane for a given moment. The technical side of the problem was taken up by dr Przemysław Bartczak, with substantive support from my side. When we succeeded in creating a tool for sky plane orienting the models, we came up with the idea to make it available for a wide community. In order to do that, we imported all available asteroid models (from the DAMIT database by Ďurech et al. 2010, among others) to our newly created "ISAM" database (Interactive Service for Asteroid Models)[1]. The first test and an example of successful utilisation of the service was correctly oriented model of asteroid 160 Una (created by Marciniak et al. 2009) and obtained good fit to double star occultation by this body observed by George et al. (2001), Fig. 4.

The sizes of studied asteroids from occultation fitting well agree with earlier determinations using data from infrared space telescopes (IRAS, AKARI, and WISE). ISAM database created by us works until present, and is being widely used e.g. by stellar occultations observers and other minor bodies researchers. It is also a good popularisation tool for planetary research and astronomy in general, allowing e.g. for displaying 3D images or easy generating animations with rotating asteroid with lightcurve generated live. It allows to track how various parts of the surface create given lightcurve features.

4.3.4 Pioneering campaign to counteract observing selection effects in asteroid studies

A great majority of studies of asteroid physical parameters before the year 2010 have been focusing on targets of short and very short rotation periods, and those of relatively large lightcurve amplitudes (e.g. Magnusson 1990, Michałowski 1996, Kaasalainen et al. 2002). Ths was caused, among other factors by relatively low quality of available then data from photometers and early CCD cameras. The exceptions here were e.g. binary asteroids, including (90) Antiope, which by their

[1] isam.astro.amu.edu.pl

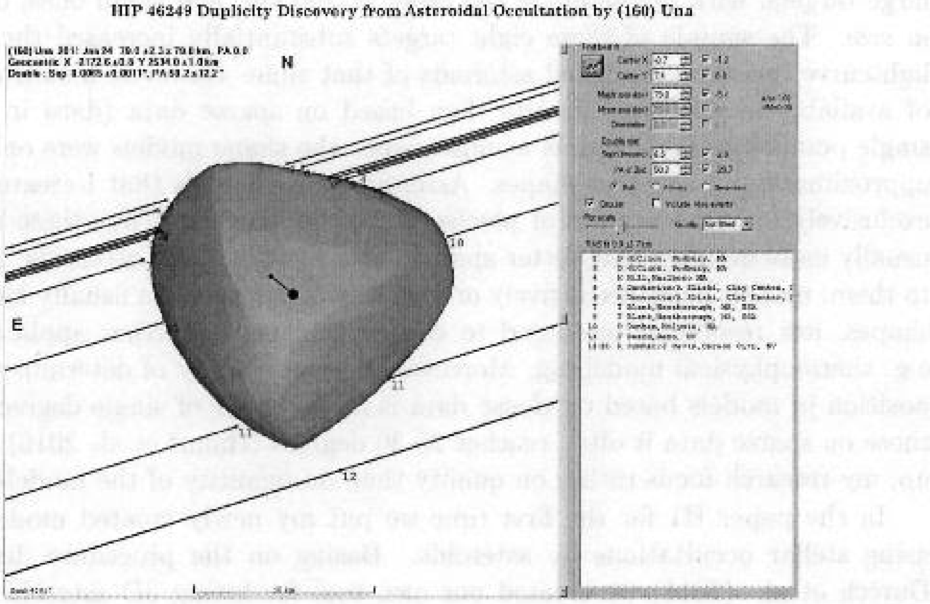

Figure 4: Occultation chords of a star HIP 46249 occulted by asteroid 160 Una, with the lightcurve inversion model by Marciniak et al. 2009 superimposed. This event independently confirmed spin parameters and shape model from the lightcurve inversion method (George et al. 2011).

nature have mutual orbital periods of their components of the order of at least 15 hours (Michałowski et al. 2004) and precessing asteroids, like Toutatis (Hudson and Ostro, 1998). Single asteroids with rotation periods longer that 10-12 hours and amplitudes not exceeding ~ 0.2 magnitude have been considered then only a few difficult cases, not worth caring for. This view has been widespread due to e.g. important work by Pravec et al. (2002), which proved that an average rotation period, for asteroids where this value was known, was around 8 hours. The key word here is „known". In asteroid rotation studies a widely used resource is the "LCDB" database[2] created and updated by Warner et al. (2009). It collects all the literature data on physical parameters of asteroids. Then, in 2002, the rotation periods have been determined only for less than a thousand of asteroids, and for practically none of asteroid groups have the knowledge of rotation parameters been complete. More than 15 years later LCDB (version from 31 January 2019) denotes more than 20 thousand of asteroids with known rotation period. Also, now it can be said that almost all main belt asteroids brighter than H=11 magnitude (which translates into sizes down to 30 km), have determined rotation periods (see Fig. 1).

Analysing this well studied group I discovered that an average rotation period is not anymore around 8 hours, but now it is substantially longer, reaching as much as 20 hours. Median rotation period in this group is almost 11 hours (H2). The maximum amplitudes observed for these targets show similar tendencies: as noticed by Warner and Harris (2011), for 40% of asteroids with periods considered reliable in LCDB, their lightcurve amplitude never exceeds 0.2 magnitude. It indi-

[2] The Asteroid Lightcurve Database,
http://www.minorplanet.info/lightcurvedatabase.html

rectly influences the correctness of period determinations and further perspectives for such determinations in the light of emerging massive sky surveys, providing data of the sparse character (of the order of 1-3 datapoints per day). Median maximum amplitude for the sample defined above is 0.27 magnitude (Marciniak et al. 2015 – H2).

Summing up, nearly half of the well studied asteroid population rotates with periods considered long (above 12 hours), practically impossible to be fully covered during single observing night, and similarly numerous group displays small or very small amplitudes (not exceeding 0.25 mag), requiring photometric precision of the order of hundredths and thousandths of a magnitude. After discovering these facts I decided to set up an observing campaign for targets having both of these features at the same time, that is bright main belt asteroids with slow rotation and small amplitudes, in order to decrease both selection effects possibly most effectively. The programme obtained support from Polish National Science Center through scientific project of the type SONATA, entitled "Against the observational bias in spins and shapes of asteroids", led by myself. It was aimed at gathering photometric data fully covering rotation period for all of a few tens of chosen asteroids in each apparition, until these data (supplemented by data from the literature), enable creating unique spin and shape models for at least e few of these bodies, using lightcurve inversion method.

These models were visibly lacking from the literature, as described in the introduction, and as a consequence an incomplete picture of spin axis distribution, rotation rates and shapes, began to emerge. All that is now known on spatial spin axis distribution and shapes of small asteroids (below 30 km in diameter) is based on studies of only a sub-sample of these targets with specific features, that enabled these parameters to be determined. One can say that it is a kind of self-fulfilling prophecy. But it is by no means a representative sample for the whole population, which is depicted by Fig. 2, which presents asteroids from the range of H=11-13 mag, which translates into sizes D $\simeq$ 37–5 km. Unawareness of the existence of these and other selection effects has far-reaching consequences, influencing currently accepted theories of dynamics and evolution of small bodies in the solar system.

In summary, the publication H2 contains a justification and initial results of the first observing campaign of the kind, focusing on unpopular, difficult targets, and going upstream nowadays mass surveys. In contrast to most of the observations available in the literature, in this campaign we conduct regular monitoring of all targets in each apparition (and not just one), not only to determine the rotation period, but also the spin axis coordinates and to reconstruct the shape. We follow them even in unfavourable observing conditions, when our targets are on low declinations or in the proximity of the Milky Way.

Back then, 8 stations from various countries participated in my campaign, and a dozen or so researchers were gathered around the idea of decreasing the selection effects in asteroid studies, which brought very good results. During the first two years of the campaign, almost 1700 hours of data were gathered, with a photometric precision of a few hundredths and thousandth of a magnitude. Its first, unexpected result was that at least 1/4 of the studied population had previously incorrectly determined rotation periods, often by a factor of 3/2 or even 2. So apart from the above described selection effects I came across another effect distorting the distribution of known rotation rates e.g. versus sizes. This percentage must certainly be even larger for fainter targets, which must strongly distort the lower part of the well known size – rotation frequency plot (Fig. 5). This in turn, influences the simulations of collisions and thermal effects and based on them theories of dynamics and physical processes that minor bodies of the solar system undergo.

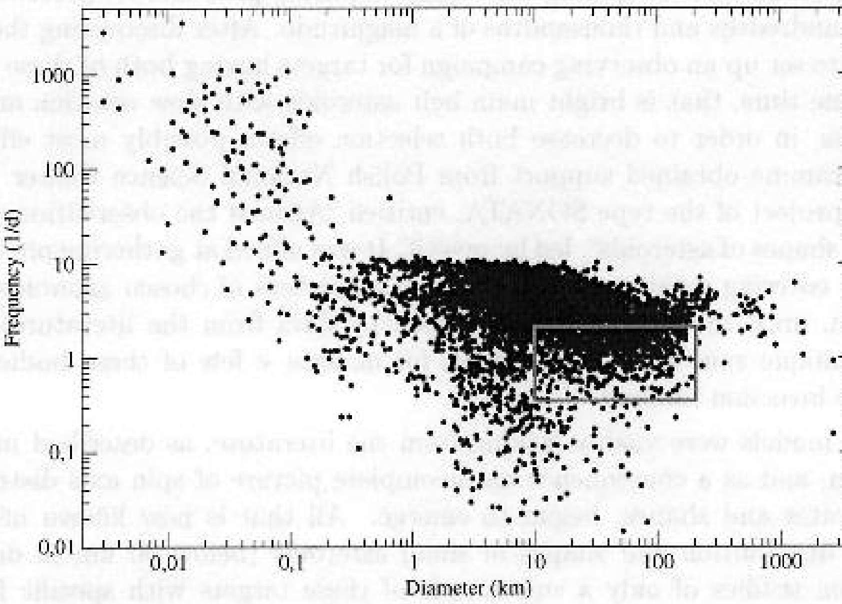

Figure 5: Plot of asteroid rotation frequencies versus their sizes (after: Warner et al. 2009). The red frame denotes targets studied in the project of Marciniak et al. (2015) – H2.

4.3.5 Synergistic asteroid studies in the visible and infrared, verification of the modelling techniques

In the year 2017, after four years on an extensive campaign, gathered observational material has been rich enough to enable creating full spin and shape models for the first five targets of the studied sample (creating a unique model of an asteroid requires full lightcurves from at least five distinct apparitions).

In the publication H3 I presented results of asteroid modelling with two different lightcurve inversion methods, which is quite unique, using already classical convex inversion (Kaasalainen and Torppa 2001, Kaasalainen et al. 2001) in parallel with SAGE algorithm ("Shaping Asteroids with Genetic Evolution", Bartczak and Dudziński 2018), recently created in our institute. The latter method has been previously verified on only two real targets, so additional five cases helped to lend credence and ground the SAGE algorithm. Using the former method I constructed convex versions of shape models for the studied here targets. The results are quite interesting: obtained spin parameters are in agreement within their error bars, while shape models sometimes quite differ (compare models of 227 Philosophia and 39 Svea in Figs. 5 and 6 and in Figs. 7 and 8 in H3). Other shape models obtained here confirm previously known fact, that large planar areas of convex shape models usually represent concavities on asteroid surfaces. Apart from those places, models from both techniques are usually consistent (compare Figs. 3 and 4, 9 and 10, and 11 and 12 from H3).

Not content with obtaining just scale-free shape models, in the work H3, we fitted the models to the available multi-chord stellar occultations from the NASA Planetary Data System (Dunham et al. 2016), as a result determining the sizes of two studied asteroids. Thanks to this technique it was also possible to identify clearly preferred spin axis solution for asteroid 329 Svea from two possible pole solutions. Such mirror-symmetric pole solutions are intrinsic to lightcurve inversion based models (compare Fig. 19 and 20 in H3). Moreover, stellar occultations evidently confirmed some nonconvexities of the SAGE shapes: chords from occultation timings collectively probe the shape cast on Earth by an occulting body, and our shape models appered to fit those shapes (see Fig. 19 in H3). In it worth mentioning here, that we created those shape models using only disk-integrated photometry, that is observing our targets as point-like sources. This results is especially important in the light of works arguing that unique modelling of nonconvex shape features is not possible, as lightcurves of main belt asteroids were considered to lack the signatures of such features (Ďurech and Kaasalainen 2003, Viikinkoski et al. 2017).

Another innovative aspect of the described here paper is successful application of the obtained spin and shape models in thermophysical modelling, simultaneously using infrared data from three different space observatories (IRAS, AKARI, and WISE). Very good fits to thermal data were obtained, in spite of calibration problems in each of the facilities alone, and in cross-calibration between them. Moreover, very small deviations and lack of trends in O-C diagrams versus wavelength, phase angle, and rotation angle prove the good quality of our spin and shape models (see e.g. Fig. 15 in H3). Also, thanks to the use of thermal data we succeeded in identifying clearly preferred pole solution for another two asteroids. These results became an important contribution to determining conditions for thermal infrared dataset, so that it enables unequivocal identification of correct pole solution. These issues were one of main science objectives for Horizon 2020 project „Small Bodies: Near And Far" (Müller et al. 2018), where I was a local coordinator. It occurred, that such a dataset needs to contain infrared data obtained both before and after opposition, but also coming from different aspects (viewing geometries) of the body. The wide range of used infrared wavelengths is of lesser importance. This knowledge will help in planning future infrared observations in the instruments like VLT/VISIR or SOFIA.

Thermophysical modelling also enabled precise determination of sizes of all studied targets, consistent with sizes from stellar occultations, and positive verification of both our shape models, and also the inversion methods used to create them.

One of the main motivations for such synergistic approach to asteroid studies was to verify the thesis on thermal inertia growth with rotation period (Harris i Drube, 2016). Thermal inertia has been determined at that time for only two slowly rotating asteroids (Delbo et al. 2015), the remaining values being only estimates. It turned out that targets studied in my survey are in many ways those most needed. The values of thermal inertia determined by us in H3 occured to be large (~100 SI units[3]) and medium (~ 50 SI units), what seemed to confirm the above mentioned thesis.

In the paper H3 I also presented another sample of slow rotators lightcurves with small amplitudes, which occurred to have previously wrongly determined spin periods. This confirmed the finding of H2, that such errors burden at least 1/4 of the studied population. It is worth noting one target (830 Petropolitana) of this sample, that already even had available model in the literature. However it turned out to rotate with period as long as 169 hours, instead of 37 hours, proving that model wrong, and revealing weaknesses of the approach to modelling based exclusively on sparse data (Hanuš et al. 2016).

4.3.6 Thermal properties of slowly rotating asteroids

The work H4 continued the approach proposed in H3, however on a larger sample of targets. I decided to perform further shape modelling only with the convex inversion method, due to its better uniqueness and stability and lesser demands on CPU time. Also, as I proved in the previous paper, both types of models – convex and nonconvex – behave similarly in thermophysical modelling.

In this paper I managed to create unique spin and shape models for 11 long-period and low-amplitude asteroids. I used data worth of hundreds of hours of photometric observations for each target, mainly gathered in my project, which in the meantime grew to 20 sites from 12 countries (plus also Kepler Space Telescope in K2 mode, thanks to the time in campaigns C14 – C19 allocated for my observing proposals). Here however, instead of verifying particular shape features, I focused rather on thermophysical aspect of studied targets. Obtained models of spin parameters and shapes are positively verified anyway, in the thermophysical modelling process, because they provide good fits to thermal data, both in the rotational phase and in flux intensity. Synergy of studies in the visible and in the infrared again brought very good results: we successively determined precise sizes of all studied asteroids, their albedos and, for all but one target, managed to determine their thermal inertias. It was quite a surprise though, that most of studied bodies this time displayed small and very small values of thermal inertia (3 – 15 SI units), while only a few showed medium values (~40 SIu), and none had high thermal inertia (~100 SIu). Careful check of all the procedures on a few previously studied targets ensured us in the reality of the obtained results. Even though we expected large values of thermal inertia, generally, in the works H3 and H4, we obtained large range of values, similarly to meanwhile published work by Hanuš et al. (2018). Our sample of 15 targets enlarged the available sample of slow rotator asteroids with known thermal inertia by as much as 50%. In the end these results denied the thesis by Harris and Drube (2016) of thermal inertia growth with rotation period (Fig. 6). It means that the heat wave must penetrate only shallow sub-surface layers, or alternatively, that infrared data from the range of 3.4 – 100 μm do not bear signatures of deeper layers. There are, however, strong indications that these layers are denser (Gulkis 2012, Keihm i Langseth 1975), but on the other hand they must also be cooler, so the joint influence of both effects on overall thermal inertia can balance out.

Thanks to years long observing campaign targeted at previously omitted aster-

[3] $[\mathrm{Jm^{-2}s^{-0.5}K^{-1}}]$

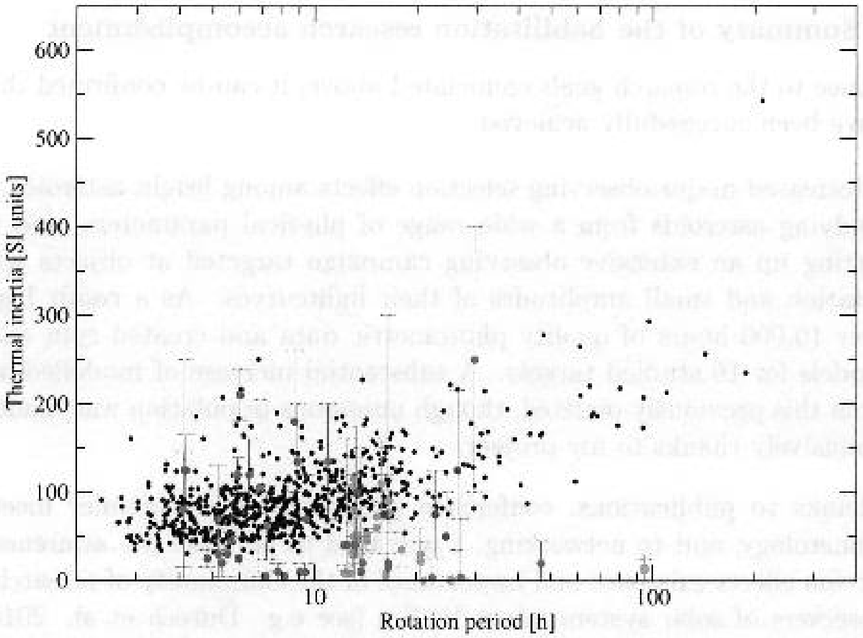

Figure 6: Updated plot of asteroid thermal inertia dependence on size, from the work by Harris and Drube (2016). Black dots are estimated values on the basis of WISE data, red points are previously available determinations from detailed thermophysical modelling (compiled by Delbo et al. 2015), and orange points are new determinations for slow rotators by Hanuš et al. (2018), based on models modified by bootstrapping method. Blue points denote values from H3, and green from H4. Thermal inertia growth with period did not confirm (Marciniak et al., in press – H4).

oids, and incorporating this research into the framework of Horizon 2020 SBNAF project, we managed to decrease adverse observing selection effects, that turned out to be important not only in the asteroid studies in the visible, but also in the infrared range. In all, in the papers H3 and H4 I increased the sample of low-amplitude slow rotators with spin and shape model by 33%, and those with known thermal inertia by 50%. Also, unlike in most of earlier works presenting asteroid models (Kaasalainen et al. 2003; Hanuš et al. 2011, 2016; Marciniak et al. 2009), all the studied here targets have been precisely scaled. Thanks to good quality and quantity of dense lightcurves, asteroid shape models based on them, together with their size determinations can serve for precise density calculations, when reliable mass determinations become available. It is worth noting that a few targets studied in my project – 100 Hekate, 301 Bavaria, 468 Lina – are on the list of ~150 asteroids with masses expected from Gaia mission. Density in turn, is one of the most important and most needed of asteroid parameters, enabling studies of their internal structure, and for bodies larger than 100 km in diameter – even their mineralogical composition. The latter are considered intact since formation (Morbidelli et al. 2009), while smaller bodies underwent collisional disruptions and reaccumulations, creating a loose structure of rubble pile, with substantial contribution of voids in their interiors (Carry 2012, Scheeres et al. 2015).

4.3.7 Summary of the habilitation research accomplishment

In reference to the research goals enunciated above, it can be confirmed that all of them have been successfully achieved:

1. I decreased major observing selection effects among bright asteroids, first by studying asteroids from a wide range of physical parameters, and then by setting up an extensive observing campaign targeted at objects with slow rotation and small amplitudes of their lightcurves. As a result I gathered over 10,000 hours of quality photometric data and created spin and shape models for 16 studied targets. A substantial increase of modelled asteroids from this previously omitted, though numerous population was made almost exclusively thanks to my project.

2. Thanks to publications, conference presentations on premier meetings in planetology, and to networking, I managed to increase the awareness of selection effects existence and importance in the community of researchers and observers of solar system minor bodies (see e.g. Ďurech et al. 2016, 2018, Cibulková et al. 2016, Molnár et al. 2018). Currently there are as many as 25 observing stations form 15 countries on 5 continents participating in my project what results in regular monitoring of tens of such "difficult" targets. In reference to my research a PhD thesis has been done, presenting statistical approach to the problem of selection effects, additionally identifying bias of the inversion method itself (Cibulková 2017).

3. My current research, in contrast to those from my PhD thesis, present interdisciplinary approach, joining models based on visible photometry with data in the infrared range of spectrum (using both ground-based observations and those from space) and with stellar occultations by asteroids (using both professional and amateur observations). It results in e.g. precise size determinations. This way I obtain broader picture of studied targets.

4. Slowly rotating, bright asteroids with small brightness changes make perfect calibration sources for infrared observatories, however so far there has been few models of such bodies. All the models that I created and data used for that are publicly available, in the following databases: DAMIT[4], CDS[5], and the infrared observations database, created within SBNAF project[6]. Additionally, ISAM service[7] of my co-authorship helps in predicting stellar occultations by asteroids and fitting available models to results from these events.

5. My sample of models applied in thermophysical procedures resulted in twofold increase in number of slow rotators with thermal inertia determined. Data for such targets have been much awaited (Delbo et al. 2015, Harris and Drube 2016). Obtained values in all occurred to have a wide range, this way I denied the thesis of thermal inertia increase with spin period. It means, that in the infrared data from the wavelength range of 3.4 – 100μm the effects of more compact sub-surface layers do not manifest themselves.

[4] http://astro.troja.mff.cuni.cz/projects/asteroids3D
[5] http://cdsarc.u-strasbg.fr
[6] https://ird.konkoly.hu/
[7] http://isam.astro.amu.edu.pl

5 Other research interests and achievements

My other research interests pertain e.g. main belt asteroid imaging with adaptive optics, observing stellar occultations by transneptunian objects, studying binary asteroids and those belonging to asteroid families in order to detect thermal effects (Yarkovsky drift, and YORP effect), and also seeking for V-type objects outside Vesta family. Recently I have also been interested in various methods of asteroid thermophysical modelling, besides classical approach presented in H3 and H4, also simultaneous optimisation of shape and thermal parameters, and also statistics-based search for optimal shape solutions using infrared data.

In my earliest research I was involved in observing binary asteroids (90 Antiope, 809 Lundia, 22 Kalliope, 939 Isberga, among others) and those from Flora family. I participated in discovery of a binary nature of asteroid 809 Lundia, and many years long campaign of mutual events in the system of 90 Antiope. Binary asteroids offer unique possibility for precise mass and density determinations, thus allowing to study their internal structure (Michałowski et al. 2004, Kryszczyńska et al. 2009, Bartczak et al. 2017). On the other hand, studies of asteroid family members enables e.g. their age determinations, identifying sources of near Earth asteroids (NEAs), and discovering "spin clusters" (Kryszczyńska et al. 2012). I have been involved in such studies in the years 2004 – 2013, participating in national research projects led by prof. Tadeusz Michałowski, prof. Agnieszka Kryszczyńska, and by dr. Przemysław Bartczak.

My important contribution to this area was e.g. bringing the lightcurve inversion method created in University of Helsinki (Kaasalainen et al. 2001) to Polish grounds, passing the know-how to researchers and students. My PhD thesis is the only available source on lightcurve inversion written in Polish and is being widely used. It resulted in a few publications (Kryszczyńska 2013, Marciniak et al. 2012 – H1, Oszkiewicz et al. 2019) and in starting a cooperation with asteroid research group fron Charles University in Prague (Ďurech et al. 2007, Marciniak et al. 2007, Hanuš et al. 2013, 2016).

Besides creating a worldwide network of small telescopes and engaging around 50 observers to my project, since more than 10 years I have been coordinating the local observers group, making continuous observations with photometric telescope in the Borowiec station, for various projects. For many years I have also been doing the data reductions, archiving all the data gathered in that station, and trained new observers, engaging bachelor students into scientific work.

I am an active observer, I had multiple observing runs in SAAO in South Africa, and in the Canarian Observatories on Tenerife and on La Palma. I also regularly observe in the local station in Borowiec. I participated in multiple observing campaigns, e.g. targeted on asteroids with non-typical polarimetric properties, (Devogèle et al. 2017), binary asteroids (Carry et al. 2015), and near Earth asteroids (Müller et al. 2017). Recently I have also been observing candidate gravitational microlensing events, participating in Gaia alerts observers network.

I am also active in the pro-am collaborations – a few stations in my network are amateur observatories. I also recently joined International Occultation Timing Association(IOTA)[8], where most members are advanced amateur astronomers, gathering precise data from stellar occultations by asteroids of great scientific

[8] http://www.asteroidoccultation.com/observations/

value. I participated in the observing campaign resulting in discovery of a ring around dwarf planet Haumea (Ortiz et al. 2017), and in the first precise size and shape determination of Himalia, an irregular satellite of Jupiter (Gomes-Junior, in preparation), among other occultation campaigns.

For two years now I have been involved in ESO Large Programme on VLT (PI: Pierre Vernazza, Aix-Marseille University), which, thanks to modernised adaptive optics techniques on large telescopes, reaches from studying global asteroid shapes to the field of planetary geology (Fetick et al. 2019). It allows us to detect separate craters on larger asteroid surfaces and link them to particular families creation events or to specific types of meteorites (Vernazza et al. 2018, Viikinkoski et al. 2018, Carry et al. 2019). My role in this programme is to deliver photometric data, that complement adaptive optics images in one modelling process with ADAM algorithm (All Data Asteroid Modelling, Viikinkoski et al. 2015).

Currently I also participate in SONATA project supported by National Science Center (PI: dr. Dagmara Oszkiewicz) entitled „Inner Main Belt V-type asteroids as tracers of differentiated planetesimals", where my role is to conduct part of the photometric campaign and do spin and shape modelling in order to determine senses of rotation of our targets (Oszkiewicz et al. 2017 i 2019). Sense of rotation governs past history of small asteroids – via the Yarkovsky drift in particular – and it might enable to detect their origin: a basaltic parent body other than Vesta, that so far has not been found, in spite of multiple theoretical premises predicting ancient existence of many differentiated planetesimals.

Thanks to good skills in professional English language, I often help in proofreading of texts written in this language. I also participated in conference translations, and have been working as translator of popular science movies, bringing TV series "The Universe" by The History Channel to Polish audience.

6 Summary of scientific output

I authored and co-authored 33 publications from Journal Citation Reports (JCR) part A, 26 of which were published after my PhD degree. I also co-authored 20 other publications and data catalogs, not counting the conference abstracts. Cumulative citation count of these papers according to Web of Science is 272. Citation count excluding self-citations is 201. Total Impact Factor (source: JCR database) of all the publications according to their publication year is 187,865. My Hirsch index (source: Web of Science) is 10.

I participated in 7 research projects funded by The State Committee for Scientific Research, Ministry of Science and Higher Education, National Science Center, and European Commission 7th Framework Programme for Research. I was a PI of one national project, and a local coordinator in one international project. I do research within in 3 research consortia.

My international collaborations (e.g. with researchers from Max Planck Institute in Germany, Hungarian Academy of Sciences, Charles University in Czech Republic, Institute of Astrophysics of Andalusia in Spain, and Aix-Marseille University) resulted in access and effective utilisation of data from space observatories (IRAS, AKARI, WISE, Kepler, TESS) and in joining world leading team studying trans-Neptunian objects, but also in access to most advanced asteroid imaging (VLT/SPHERE) and modelling methods. The results of the latter has been recently published twice in an electronic issue of *Astronomy & Astrophysics.*

I actively participated in 10 international scientific conferences and in 6 local ones, where I presented 8 oral and 8 poster contributions. I also co-authored other 9 oral and 19 poster contributions presented on 17 international conferences. During the last 3 years I also actively participated in 6 science meetings of international working group for project „Small Bodies: Near And Far" in EU-funded Horizon 2020 programme. I had 10 research stays in foreign research institutions: University of Helsinki (Finland), South African Astronomical Observatory (South Africa), Instituto de Astrofísica de Canarias (Spain) and Charles University (Czech Republic). I am a member of Polish Astronomical Society, International Astronomical Union, and International Occultation Timing Association (IOTA).

I co-organised 6 international and local conferences (being a SOC member in one of them). I also chaired 5 conference sessions.

I reviewed 4 manuscripts from JCR list A journals ("Astronomy & Astrophysics", and „Earth, Moon and Planets"), and one from „Acta Societatis Metheoriticae Polonorum". I reviewed one PhD thesis from foreign institution. I also evaluated two observing proposals within OPTICON network (Optical Infrared Coordination Network for Astronomy).

As for an education experience, I taught 3 kinds of full-semester lectures, 7 types of laboratories and 8 types of classes, for astronomy, physics and geography students. I supervised two bachelor and one master's thesis, and co-supervised another master's thesis. I gave 14 lectures for the wide audience and actively participated in more than 20 sky shows and popularisation events. I gave 8 invited talks in Polish institutions, and one at a local conference. I also took part in two films for popularisation of astronomy.

To upgrade my qualifications I participated in summer school on astrostatistics and large astronomical databases, in a course on modern methodology for physics teaching, in a course of professional English, and in Python programming course.

I have been awarded 4 collective science awards by Rector of Adam Mickiewicz University, and one individual Rector's scholarship for outstanding scientific achievements. I was also granted scholarships for young doctors and for unique alumni, and Faculty of Physics Dean's award for works on new education programs. I have also been awarded a motivating perquisites for scientific achievements and for successful grant applications. In April 2017 IAU Working Group for Planetary System Nomenclature has assigned name 'Marciniak' to asteroid number 10471, for my contribution in studies of long-period main belt asteroids.

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