HABILITATION SUMMARY

1. Name: **Szymon Kozłowski**
2. List of all scientific degrees:
   (including name, place, and date of obtaining; provide the PhD thesis title)
   (a) **Master of Science (MSc)**, physics (specialty: astrophysics), The University of Zielona Góra, 2004
   MSc thesis entitled "Deriving parameters of extrasolar planets"
   (b) **Doctor of Philosophy (PhD)** obtained on 3 October 2007 at the Faculty of Engineering and Physical Sciences, The University of Manchester (UK). Nostrification validated by the Faculty of Physics of the University of Warsaw on 12 April 2010 (Certificate 2/2009/2010 from 13 April 2010).
   PhD thesis entitled "Gravitational microlensing in the Milky Way with the Hubble Space Telescope and OGLE-III", supervisor prof. Shude Mao
3. Employment:
   (a) Jodrell Bank Observatory, The University of Manchester, UK
   PhD student, 2004–2007
   (b) Department of Astronomy, The Ohio State University, USA
   postdoctoral researcher, 2007–2010
   (c) Astronomical Observatory, University of Warsaw, Poland
   postdoctoral researcher, 2010–present
4. Habilitation achievement
   (a) title:

Quasars behind the Magellanic Clouds – new candidate selection methods and their quantification

   (b) author(s), title(s) of publications, year of publishing, journal name:
   1. **Kozłowski S.** & Kochanek C. S., "Discovery of 5000 Active Galactic Nuclei Behind the Magellanic Clouds", 2009, The Astrophysical Journal, 701, 508; cited 27 times (ADS)
   2. **Kozłowski S.**, Kochanek C. S., Udalski A. et al., "Quantifying Quasar Variability as Part of a General Approach to Classifying Continuously Varying Sources", 2010, The Astrophysical Journal, 708, 927; cited 55 times (ADS)
   3. **Kozłowski S.**, Kochanek C. S. & Udalski A., "The Magellanic Quasars Survey. I. Doubling the Number of Known Active Galactic Nuclei Behind the Small Magellanic Cloud", 2011, The Astrophysical Journal Supplement, 194, 22; cited 9 times (ADS)

4. **Kozłowski S.**, Kochanek C. S., Jacyszyn A. M et al., "The Magellanic Quasars Survey. II. Confirmation of 144 New AGNs Behind the Southern Edge of the Large Magellanic Cloud", 2012, The Astrophysical Journal, 746, 27; cited 12 times (ADS)
5. **Kozłowski S.**, Onken C. A, Kochanek C. S. et al., "The Magellanic Quasars Survey. III. Spectroscopic Confirmation of 758 AGNs Behind the Magellanic Clouds", 2013, The Astrophysical Journal, 775, 92; cited twice (ADS)

(c) presentation of research goals, results and resulting publications, implications for future work:

Introduction

Active Galactic Nuclei[1] (AGNs) are the brightest continuous sources of radiation in the Universe, visible far from its observable edge. They are of key importance both as tools in understanding the history and evolution of the Universe, but also as probes of low- and high-energy astrophysics. There is over 200 000 AGNs discovered to date, a fair fraction coming from the Sloan Digital Sky Survey (SDSS). Based on a single epoch observation from SDSS, a number of basic AGN parameters have been determined, including black hole masses, redshifts, or Eddington luminosities. There are 9000 AGNs, however, that SDSS observed 60 times over eight years baseline that enabled studies of quasar variability as a function of physical parameters (MacLeod, Ivezić, Kochanek, **Kozłowski** et al. 2010, publication cited 72 times).

It was recently realized that there must exist a large number of well-monitored quasars, that have been observed by microlensing surveys, but they have never been identified. The OGLE project has been monitoring the Magellanic Clouds since 1997, so the time baseline spans 16 years. Since 2001, in its third phase, OGLE has monitored approximately 55 square degrees of the Magellanic Clouds. Such an area should contain approximately 1300 AGNs brighter than $I < 20$ mag assuming the quasar luminosity function from Richards et al. 2006.

Finding quasars in such dense stellar regions is difficult. The estimated number of AGNs brighter than $I < 20$ mag per square degree is $\sim$25, while the corresponding number of stars in the same area of the sky would be of order of one million. Difficulties in finding quasars among millions of the Magellanic Clouds' stars were reflected in a very low detection number – 80, after numerous research projects in the last two decades (Schmidtke et al. 1994, Eyer 2002; Dobrzycki et al. 2002, 2003ab, 2005; Geha et al. 2003).

As my habilitation achievement, I present my contribution to this field of research. I designed two new methods of finding quasars in dense stellar fields and then used them to discover 713 new AGNs – increasing their number by an order of magnitude in the observed area of the sky. These AGNs will be of key importance to understanding physical processes in AGNs (based on the long-term high-cadence photometric observations from OGLE – the only sample with such temporal coverage), but also for deriving proper motions of the Magellanic Clouds and studying the interstellar absorption.

[1] The terms AGNs and quasars will be used interchangeably throughout the text.

New AGN selection methods

In 2009, I worked with Chris Kochanek on modification of a mid-IR method of selecting quasars that was primarily used in extragalactic astrophysics (Stern et al. 2005) and expanded it for use in dense stellar fields. Our method is based on a joint analysis of mid-IR data from the Spitzer Space Telescope and optical data from OGLE. Spectra of quasars are very characteristic in mid-IR but also very different from most stars and galaxies. Building color indices $[3.6]-[4.5]$ and $[5.8]-[8.0]$ allows to separate quasars from stars and galaxies by using "the AGN wedge" (Figure 1, left panel). The second criterion is based on the localization of objects on the color-magnitude diagram ($[3.6]-[8.0]$, $[8.0]$). Quasars occupy a somewhat different region in that space than stars and galaxies, however, dusty stars (young stellar objects, planetary nebulae, Be stars) can partly occupy similar space to quasars (Figure 1, right panel). The final criterion is the $I-[8.0]$ color, that enables removal of a fair fraction of these stars. In publication (1), we introduced a three-step criteria to select quasars and provided a list of 5000 AGN candidates. In the final publication (5), we show that 27% of these candidates turned out to be quasars (44% for bright candidates $I < 19.5$ mag), which proves the method is very efficient.

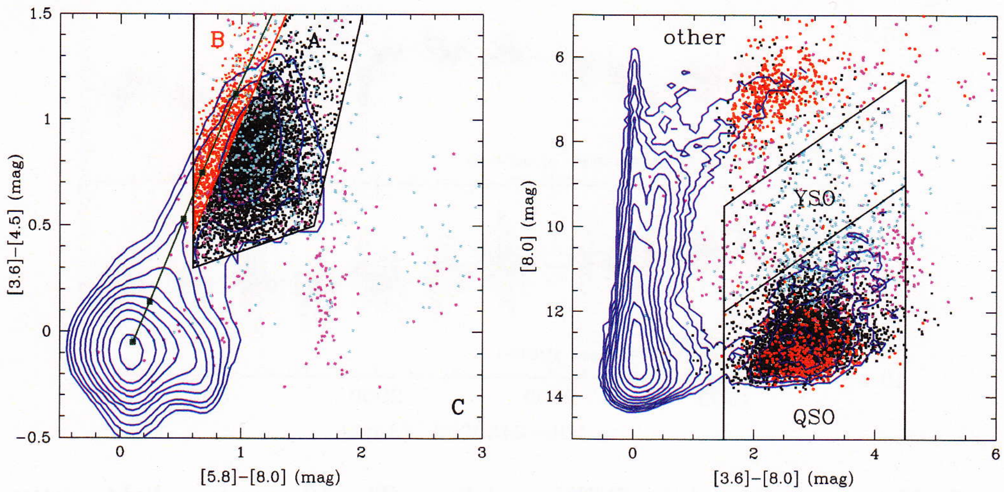

Figure 1: Mid-IR color-color (left panel) and color-magnitude (right panel) diagrams for objects observed with the Spitzer Space Telescope in the direction of the Magellanic Clouds. Smoothed contours are for 2, 5, 10, 20, 50, 100, 200, 500, 1000 and 2000 objects in a bin size of 0.1 mag for color and 0.2 mag for magnitude. *Left panel:* Stars are clumped near colors (0, 0), while AGNs are inside the AGN wedge (thick solid black line) and are marked with black for pure sample and red for a sample containing cold stars. The remaining points are confirmed or high-probability young stellar objects (YSO). *Right panel:* In this space, quasar candidates are separated from stars (contours) and most YSOs, using the two proposed selection areas: YSO – containing mostly young stellar objects and QSO – containing mostly quasar candidates.

Kelly et al. (2009) showed that aperiodic photometric light curves of quasars can be "reduced" to two parameters only: an amplitude σ and a time scale τ when using the Damped Random Walk (DRW) model. In publication (2), we showed that DRW described quasars light curves very well (with residuals on a 0.01–0.02 mag level; Figure 2) using a small sample of quasars from OGLE. In particular, in that paper I analyzed the variability of common types of variable stars and presented several criteria for selecting quasars based on DRW model parameters. In publication (2), we proposed a few-step procedure to select quasars based on the variability parameters from the DRW model. The key selection step, in the $\hat{\sigma}/\tau$ space, is shown in Figure 3.

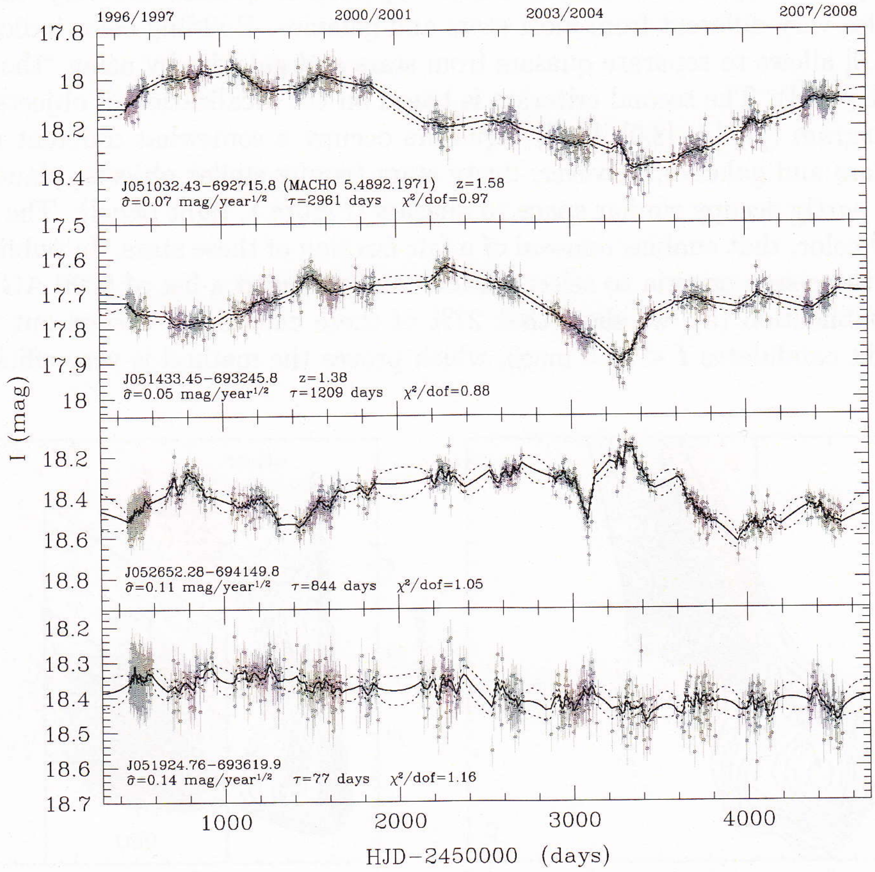

Figure 2: Four examples of the DRW modeling. The 12-year-long light curves are from the OGLE-II and OGLE-III survey (years 1997-2008). The two upper panels show confirmed quasars, while the two lower ones show objects with different types of variability. The black solid line represents the best fitting DRW model, while the area between the two dashed lines represents the 1σ range of plausible stochastic models.

The methods presented in the two discussed publications were used to select quasar candidates. I added another criterion, requiring the X-ray emission by the candidate. I analyzed 50 million light curves from the OGLE-III project using the DRW modeling. I selected 1100 (300) variable quasar candidates behind the LMC (SMC).

Spectroscopy of quasar candidates

In 2009, we established a spectroscopic survey of the Magellanic Clouds named *The Magellanic Quasars Survey* (MQS), for which I am the Principal Investigator (PI). In the first pilot observations we observed one field (3 square degrees) in the Small Magellanic Cloud containing

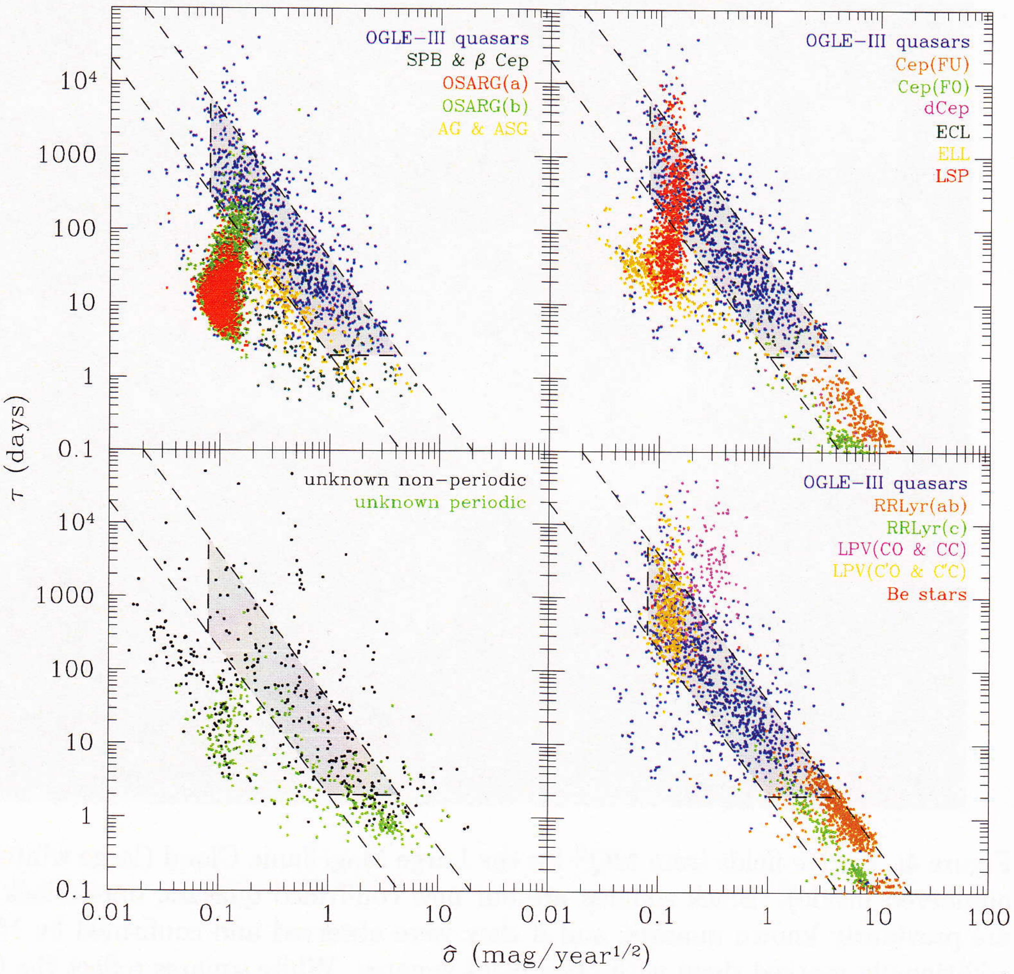

Figure 3: We defined a trapezium cut (gray area) in the $\hat{\sigma}$-τ space containing the majority quasar candidates (blue points) from publication (1). The four panels show exactly the same area but contain different classes of variable objects (other colors). Additional cuts presented in publication (2) remove most of the unwanted stellar contamination.

268 candidates selected with the three described methods. We spectroscopically confirmed 32 quasars including 29 new ones, but we also classified 12 objects as plausible quasars. These findings were presented in publication (3).

In 2011, in the next phase of the project, I spectroscopically observed, reduced, and analyzed data for four fields in the Large Magellanic Cloud, containing 845 quasar candidates, confirming 169, including 144 new ones (publication (4)). In January 2013, we observed the remaining fields in the LMC and 70% of the SMC. In total, during the MQS project we observed 3017 quasar candidates, of which 758 were spectroscopically confirmed as quasars. 713 of them are new quasars (publication (5)). Distribution of the confirmed quasars on the sky discovered behind the LMC is shown in Figure 4. Spectra of 50 out of 713 new quasars are shown in Figure 5. Approximately 1000 spectra have too low signal-to-noise ratio for any identification – they can still, however, be quasars. The remaining spectra seem to be that of dusty objects such as young stellar objects, planetary nebulae, and Be stars.

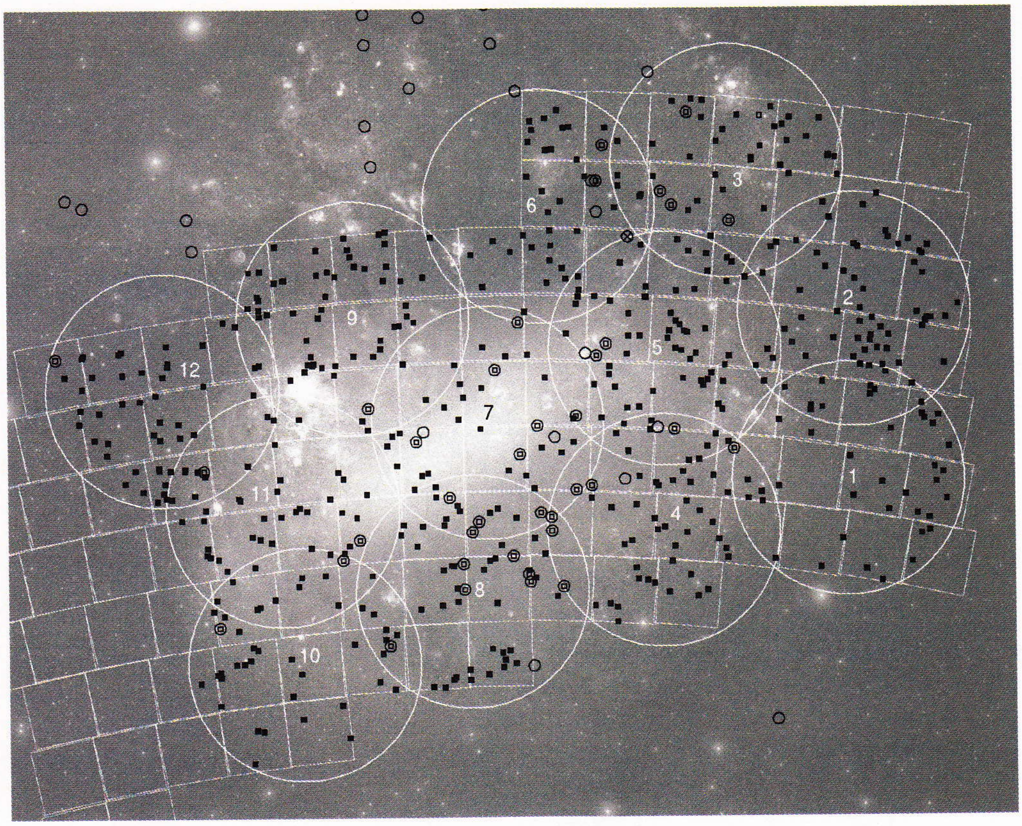

Figure 4: Twelve fields from MQS for the Large Magellanic Cloud (large white circles numbered inside). Black squares are our new confirmed quasars, open black circles are previously known quasars, and if they were observed and confirmed by MQS we additionally marked them with open black squares. White squares reflect the OGLE-III fields. The image size is 9° × 7°, North is up, East is to the left.

Quasar detection efficiency of the proposed selection methods

With the current sample of quasars and other observed sources we were able to estimate the quasar detection efficiency of the proposed methods. There were 1703 objects selected by the mid-IR method (publication (1)) and not found by the remaining two methods, of which we confirmed 300, giving 18% efficiency. There were 354 candidates selected based on DRW modeling of OGLE light curves (variability method) and not found by the remaining two methods, of which we confirmed 29 quasars, giving the yield of 8%. There were 74 objects selected by the third method (X-ray emission) and not found by the remaining two methods, of which we confirmed two. These results are not surprising if we notice that quasars "should have" all three properties simultaneously.

Combining any two methods described above and requiring a non-detection by the third method gives the following results: The mid-IR and X-ray emission methods select 113 candidates, of which 36 are confirmed quasars (32% efficiency). The mid-IR and variability methods select 641 quasar candidates, of which we confirmed 315 (49% efficiency). The variability and X-ray emission methods select 14 candidates, of which we confirmed 6 (43% efficiency). Combination of all the selection methods returned 98 quasar candidates, of which we confirmed 69,

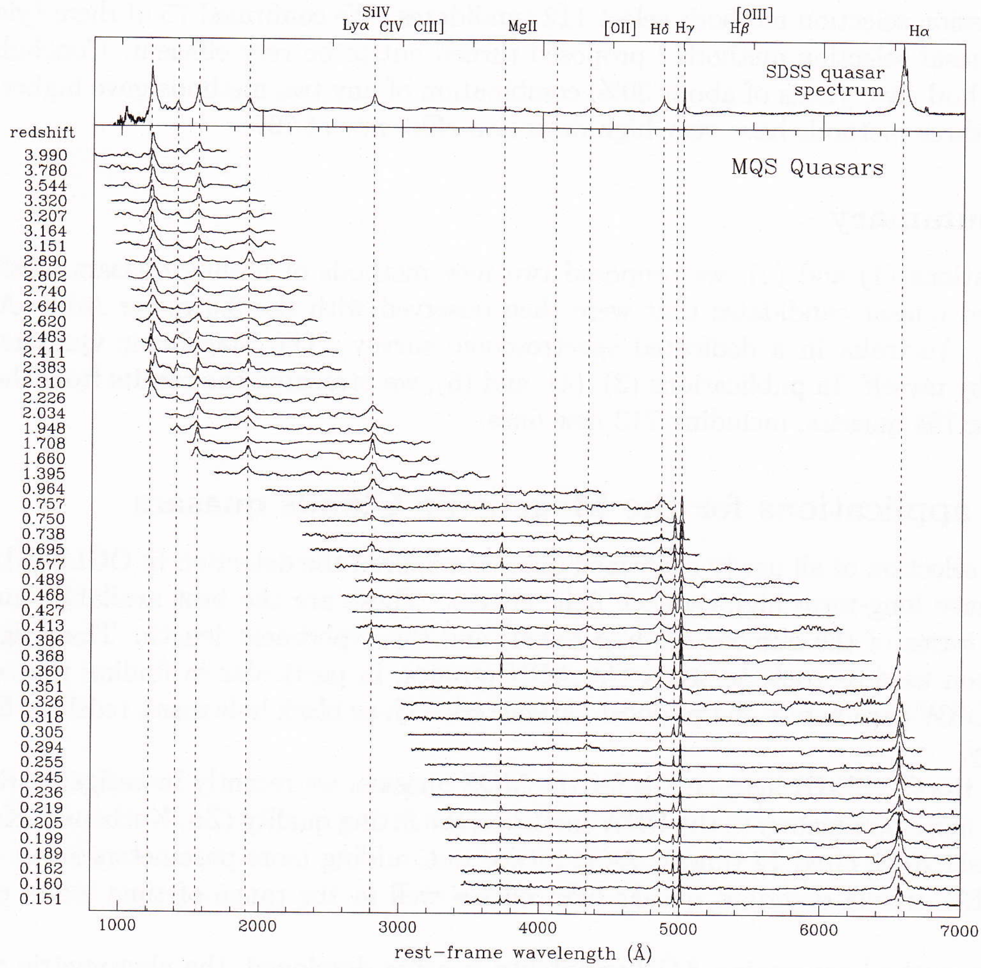

Figure 5: *Main panel:* Rest-frame spectra of 50 out of 713 new quasars discovered behind the Magellanic Clouds by the MQS. Each spectrum has a corresponding redshift shown in the left column. All major quasar emission lines are marked with dashed vertical lines with labels. *Top panel:* For comparison we show an average spectrum for 2200 AGNs from SDSS.

resulting in a relatively high detection efficiency of 70%.

The above detection efficiency results are discussed for objects that were selected either by one method and not by the remaining two methods or by two methods and not the third. It is interesting to check the detection efficiency for cases when either we select a candidate with one method and we are not interested if it was selected by the remaining two methods or by two methods and we are not interested if it was selected by the third. The mid-IR method selected 2555 quasar candidates. We spectroscopically confirmed 720, giving the detection efficiency of 27%. There were 1107 quasars candidates selected by the variability selection method. We confirmed 419 quasars, giving the yield of 34%. The X-ray emission method selected 299 quasar candidates, of which we confirmed 113 (yield 30%). Let us now discuss the combined selection methods. The mid-IR and variability selection methods select 739 quasar candidates. We spectroscopically confirmed 384 (yield 52%.) The mid-IR and X-ray emission selection methods select 211 candidates, of which we confirmed 105 (yield 49%). The variability and

X-ray emission selection methods select 112 candidates. We confirmed 75 of them (yield 66%).

The quasar selection methods I proposed turned out to be very efficient. Concluding, each single method gave yields of about 30%, combination of any two methods gave higher yields of 50%. All three methods have very high detection efficiency of 70%.

Short summary

In publications (1) and (2), we proposed two new methods of finding quasars. Using them, we selected quasar candidates that were then observed with the 3.9 meter Anglo-Australian Telescope, Australia in a dedicated spectroscopic survey "The Magellanic Quasars Survey" designed by myself. In publications (3), (4), and (5), we presented the results from the project, confirming 758 quasars, including 713 new ones.

Future applications for the Magellanic Clouds quasars

Since the selection of all newly confirmed quasars required the detection in OGLE-III, all these quasars have long-term high-cadence light curves. These are the best available quasar light curves in terms of the number of observations and the experiment length. These light curves will be soon used as tools to study the AGN physics, in particular in finding the connection between DRW parameters and physical parameters such as black hole mass, redshift, Eddington luminosity.

Using the OGLE-III light curves for the MQS quasars, we recently investigated the impact of adding more parameters to the DRW model on the fitting quality (Zu, Kochanek, **Kozłowski** and Udalski 2013; cited 12 times). As it turned out, adding more parameters is not necessary as the DRW model describes quasar light curves well in the range of time scales of days to years.

A new method concerning AGN variability is being developed, the photometric reverberation mapping, whose key idea is to search for time delays between the emission line variability and the continuum variability. The only difference between this photometric method and the well-known spectroscopic one is that the time delays are searched for in a photometric light curve containing both the line and the continuum. Chelouche et al. (2012) used the MQS data to investigate the properties of one selected quasar, for which these authors found both the time delay and the black hole mass. In collaboration with Chris Kochanek and Ying Zu, I am participating in further development of this method based on the OGLE data.

The key use of the MQS quasars will be as an astrometric grid in proper motion studies of the Magellanic Clouds. There exist research studies with the Hubble Space Telescope of proper motions for the LMC based on only 21 quasars and the SMC based on only four quasars (Kallivayalil et al. 2006a,b). The results were a surprise. It turned out that the orbits of the Magellanic Clouds are likely much larger than previously anticipated or that the Clouds are on their first passage in the vicinity of the Milky Way (Besla et al. 2007). The proper motion uncertainties, however, are dominated by the small number of quasars known behind the Clouds. In collaboration with Dr. Nitya Kallivayalil, I participate in a project of measuring the proper motion and rotation of the SMC. Recently, we obtained 120 orbits of the Hubble Space Telescope to measure proper motion and rotation of the SMC, based on 30 new quasars discovered by MQS. Based on a small number ($\sim$10) of bright quasars from MQS, we found a preliminary proper motion and a "trace of rotation" for the LMC based on the ground-based OGLE-III data (PhD thesis of Radosław Poleski, for whom I acted as an auxiliary supervisor).

We provided 50 bright quasars ($I < 18$ mag) that enable studies of the interstellar extinction in the Magellanic Clouds.

5. Presentation of the remaining scientific achievements.

In September 2004, I started my PhD studies at Jodrell Bank Observatory, The University of Manchester, UK, in an European training network ANGLES. I worked on three major projects under supervision of Prof. Shude Mao. Two of these projects were subsequently published in peer-reviewed astronomical journals. Using the software and experience from the third project, I published several scientific papers.

The goal of the first project was to measure proper motions of 26000 stars belonging to the Galactic bulge using data collected with the Hubble Space Telescope. In **Kozłowski** et al. 2006 (cited 15 times), we showed gradients in velocity dispersions of stars and also, for the first time, we measured the inclination of the velocity ellipsoid to the Galactic plane. In the second paper, **Kozłowski** et al. 2007 (cited 12 times), also for the first time, we directly observed a lens and a source separating on the sky after a microlensing event toward the Galactic bulge. I spent five months of my PhD working in the Los Alamos National Laboratory, New Mexico, USA, on the above projects under supervision of Dr. Przemysław Woźniak. Both project were also discussed with Prof. Bohdan Paczyński during my two visits to Princeton University, New Jersey, USA. Since 2004 I have been collaborating with Łukasz Wyrzykowski – member of the OGLE project. In 2005, I started a close collaboration with PIs of OGLE, Prof. Andrzej Udalski and Dr. Michał Szymański. During my PhD studies, I developed several independent data analysis pipelines with the goal of analyzing the OGLE data. The first pipeline was designed to reduce large numbers of OGLE images into calibrated light curves for all detected objects. The second pipeline was designed to find microlensing events among millions of light curves. The final pipeline was designed to test the detection efficiency of microlensing events. I injected artificial microlensing events into series of images. These images were analyzed with the use of pipeline 1 (converting images to light curves) and then the light curves were inspected by pipeline 2 in order to find microlensing events. In my PhD thesis, I analyzed one OGLE-III field, for which I measured the microlensing optical depth of $\tau = (2.91 \pm 0.77) \times 10^{-6}$, in agreement with other studies for the same region of the sky. My PhD thesis, entitled "Gravitational microlensing in The Milky Way with the Hubble Space Telescope and OGLE-III", was defended on 26 September 2007. I obtained the highest possible mark in British system (acceptance without corrections). During my PhD studies, I participated in several international astronomical conferences and workshops, where I presented my research results.

In October 2007, I began a postdoctoral position at The Ohio State University, USA under supervision of Prof. Christopher Kochanek. My duties were to collect data from the 1.3 meter SMARTS telescope, Cerro Tololo, Chile, their analysis and obtaining light curves for lensed quasars. I am a coauthor of three papers based on these data. In 2008, I became a member of the MicroFUN group (also based at the Ohio State University), a group aiming at the high-cadence monitoring of planet-sensitive microlensing events. Using the pipeline developed during my PhD studies, I analyzed data from 15 different telescopes in the MicroFUN collaboration, starting with 30 cm telescopes and including as big ones as 8 meter VLT. I am a coauthor of 17 papers based on these data, cited 273 times, and co-discovering seven extrasolar planets (MOA-2007-BLG-400Lb, MOA-2008-BLG-310Lb, MOA-2009-BLG-319Lb, MOA-2009-BLG-387Lb, MOA-2011-BLG-293Lb, and OGLE-2012-BLG-0026Lb,c).

In 2008 as a photometry expert, I was invited into one of the groups working on the Spitzer Legacy Programs entitled "The Spitzer Deep Wide Field Survey (SDWFS)". In this project I was responsible for quality of mosaic images and photometry. Each analyzed mosaic was made of 20000 small CCD images. I am the main author of one out of two key papers from this project. In this paper, I performed the Difference Image Analysis on the SDWFS data, created the catalog of 500000 variable objects, and for the first time showed the mid-IR variability of large number of quasars ($\sim$1100; **Kozłowski** et al. 2010b; cited 15 times). In the SDWFS data, however, the most variable object turned out to be a supernova – SN 2007va (**Kozłowski** et al. 2010c; cited 14 times). In this paper, we showed that SN 2007va was a truly unusual object and one of the brightest in history, emitting $\sim 10^{51}$ ergs in infrared. Supernovae emit little light in infrared, unless there are clouds of matter the ejecta can collide with. We showed that to generate $\sim 10^{51}$ ergs in infrared, the dying star had to have at least two eruptions, each ejecting 10 solar masses prior to the final supernova explosion. The ejected clouds of gas and dust efficiently converted the energy of the ejecta into infrared radiation observed in SDWFS. This discovery was sufficiently interesting to have "press release" by JPL, NASA, The Ohio State University in USA and The University of Warsaw in Poland.

I am also a coauthor of the second important paper based on the SDWFS data, where we show that the extragalactic background light is due to stars ejected from their host galaxies during galaxy mergers. This finding was published in Nature (Cooray et al. 2012; cited 8 times) and had a "press release" by JPL, NASA, The Ohio State University in USA and The University of Warsaw in Poland. Summarizing, I am the coauthor of four SDWFS papers, cited 122 times.

In 2009, when working with the Spitzer data, I noticed that the mid-IR part of the spectrum is as effective to find active galactic nuclei in dense stellar fields as it is in sparse fields (Stern et al. 2005). Quasars in mid-IR have characteristic colors and are relatively easy to differentiate from "normal" stars and galaxies. In **Kozłowski** & Kochanek (2009; cited 27 times), we analyzed data for the Magellanic Clouds collected by the Spitzer Space Telescope and published a list of 5000 quasars candidates. In another project, based on modeling of the OGLE light curves using the Damped Random Walk (DRW) model, we showed that aperiodic quasar light curves can be reduced just to two parameters: an amplitude and a time-scale. In **Kozłowski** et al. (2010a; cited 55 times), we showed that quasars occupy a different parameter space of the DRW model than other variable objects (although not entirely separated from each other). We also proposed a simple method of selecting quasars candidates based on the DRW model.

In 2009, I established an international collaboration (Poland, USA, and Australia) entitled "The Magellanic Quasars Survey" (MQS) for which I am the Principal Investigator (PI). The goal of the project was to discover as many quasars behind the Magellanic Clouds as possible. These quasars have long-term high-cadence light curves from the OGLE project and will be key to analysis of quasar variability and finding correlations between the variability parameters (from e.g. DRW) and the physical parameters. To date, we applied five times for the observing time on the 3.9 meter Anglo-Australian Telescope, Australia, obtaining a total of 11 nights. We were able to confirm 713 new quasars, and increase their number behind the Magellanic Clouds by an order of magnitude (from 80 to 800). The results from the Magellanic Quasars Survey are the basis of my habilitation achievement. The MQS papers were cited 103 times.

In 2010, I began my second postdoctoral position at the Astronomical Observatory, The University of Warsaw, Poland as a member of the OGLE team. My duties include finding and analysis of quasars, finding and analysis of transients such as supernovae and microlensing events. In October 2012, we started observing 600 square degrees in the vicinity of the Magellanic Clouds in order to find supernovae, discovering in real-time 65 supernovae during the first three months of observing. Additional 126 supernovae were found in the archival OGLE data (**Kozłowski** et al. 2013a; 3 citations). I also collaborate with Prof. Grzegorz Pietrzyński and his group (Araucaria). For their project I performed a very precise DIA photometry of 35 eclipsing binaries (in two filters). Eight of them were used to estimate the best-to-date distance to the Large Magellanic Cloud with the accuracy of 2%. The results of our research were published in Nature (Pietrzyński et al. 2013; cited 15 times) and had a "press release" by The University of Warsaw and ESO.

In 2010, as the Principle Investigator I was awarded a prestigious grant Iuventus Plus entitled "Astrophysics of quasars behind the Magellanic Clouds" (200000 PLN). In 2012, also as the Principle Investigator I was awarded my second prestigious grant Iuventus Plus entitled "New class of extrasolar planets in OGLE-IV" (200000 PLN), where I search for short microlensing events caused by free-floating planets. In 2011, I was also awarded a fellowship for young excellent scientists (2011-2014). I spent three nights observing (spectroscopy) for the Magellanic Quasars Survey in Australia and 21 nights observing for OGLE in Chile.

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