Vita Summary

1. Name: **Dariusz Graczyk**

2. Academic degrees:
   Master of Science in Astronomy, Nicolaus Copernicus University, Toruń, 1996
   Methods of averaging in celestial mechanics.

   Doctor of Philosophy in Astronomy, Nicolaus Copernicus University, Toruń, 2003
   Long period eclipsing binary stars.

3. Work with academic institutions.
   Institute of Astronomy, University of Zielona Góra, 2003
   University of Concepción, Chile, 2009- present

4. Scientific achievements:
   a. title of scientific work
      Eclipsing binary stars as distance indicators.

   b. (author, title of paper, year, publisher)

      H1. **Graczyk, D.**, 2003, MNRAS, 342, 1334
      Light-curve solutions for bright detached eclipsing binaries in the Small Magellanic Cloud: absolute dimensions and distance indicators
      Impact factor = 4.99, number of citations: 13

      H2. **Graczyk, D.**, Eyer, L., 2010, AcA, 60, 109
      The Light Curve Statistical Moments Analysis: The Identification of Eclipsing Binaries
      Impact factor = 3.49, number of citations: 4

      H3. **Graczyk, D.**, Soszyński, I., Poleski, R., Pietrzyński, G., Udalski, A., Szymański, M. K., Kubiak, M., Wyrzykowski, Ł., Ulaczyk, K., 2011, 61, 103
      The Optical Gravitational Lensing Experiment. The OGLE-III Catalog of Variable Stars. XII. Eclipsing Binary Stars in the Large Magellanic Cloud
      Impact factor = 1.68, number of citations: 21

      H4. **Graczyk, D.,** Pietrzyński, G., Thompson, I. B., Gieren, W., Pilecki, B., Udalski, A., Soszyński, I., Kołaczkowski, Z., Kudritzki, R.-P., Bresolin. F., Konorski, P., Mennickent, R., Minniti, D., Storm, J., Nardetto, N., Karczmarek, P., 2012, ApJ, 750, 144
      The Araucaria Project: An Accurate Distance to the Late-type Double-lined Eclipsing Binary OGLE SMC113.3 4007 in the Small Magellanic Cloud
      Impact factor = 6.73, number of citations: 10

      H5. Pietrzyński, G., **Graczyk, D.,** Gieren, W., Thompson, I. B., Pilecki, B., Udalski, A., Soszyński, I., Kozłowski, S., Konorski, P., Suchomska, K., Bono, G., Prada Moroni, P. G., Villanova, S., Nardetto, N., Bresolin, F., Kudritzki, R.-P., Storm, J., Gallenne, A., Smolec, R., Minniti, D., Kubiak, M., Szymański, M. K., Poleski, R., Wyrzykowski, Ł., Ulaczyk, K., Pietrukowicz, P., Górski, M., Karczmarek, P., 2013, Nature, 495, 76
      An eclipsing-binary distance to the Large Magellanic Cloud accurate to two per cent
      Impact factor = 38.60, number of citations: 30

5. **Autobiographical note**

I have been interested in astronomy since my childhood. My grandfather had a custom of walking with me in the evenings and showing me stars, planets and exploring the mysteries of

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the sky with me. We lived in a small village whose sky at nighttime was filled with hundreds of thousands of beautifully shining stars. I think that this view was and still is my inspiration for work. I attended primary school and high school in Konin. During these years, I performed some simple astronomical observations with naked eye, binoculars and different types of telescopes. Three times I participated in the National Astronomy Contest qualifying for the finals twice.

I started graduate studies in Astronomy at Nicolaus Copernicus University (UMK) in Toruń in 1990. I earned my Master's degree in 1996 after presenting a thesis devoted to a certain problem in celestial mechanics. Dr hab. Andrzej Maciejewski supervised my work.
I started my PhD studies at UMK in Toruń as well and my supervisor was dr hab. Andrzej Maciejewski and my thesis advisor was dr Maciej Mikołajeski. My PhD thesis was devoted to the eclipsing binary stars with a very long orbital period, like VV Cep and EE Cep. Participation in the 1998 conference dedicated to asteroseismology and eclipsing binary stars was an important landmark of my PhD studies. Dr Edward Guinan presented the most recent results of an analysis of the eclipsing binary star HV2274 in the Large Magellanic Cloud (LMC). Not only astrophysical parameters of both stars were derived, but above all, a precise distance to this binary was calculated, being the distance to the LMC galaxy itself. I remember that I was impressed by his speech and this influenced my scientific plans.

After the defense of my PhD thesis in 2003, I started a job as a Physics teacher in one of the high schools in Toruń. The year 2003 is important also because then, I began corresponding with prof. Bohdan Paczyński. He pointed out to me that it is an empirical star's surface brightness calibration, which would help to obtain a high precision while using the eclipsing binaries as distance indicators to nearby galaxies. At this time, I figured out that one could use long period eclipsing binaries containing late type giant stars to utilize this method and to determine the accurate distance to the Large Magellanic Cloud. I suppose that the subject of my PhD thesis was helpful to clarify this idea in my mind.

During my work in the high school, I wrote a series of popular science articles to bi-monthly magazine *Postępy Astronomii*. The articles were devoted to bright objects from the New General Catalogue by Dreyer. I also led supervised the astronomy interest groups for pupils in two highly ranked schools in Toruń. A few of my students were succeeded as the finalists and laureates of Polish National Astronomy and Physics Contests. Additionally, I continued my work on eclipsing binaries in the LMC and started collaboration with dr hab. Grzegorz Pietrzyński from Warsaw University. In 2009 I obtained a post-doctoral position the University of Concepción in Chile. There I began close cooperation with the Araucaria project conducted by prof. Wolfgang Gieren and dr hab. Grzegorz Pietrzyński. Our common effort resulted in a number of important papers dedicated to stellar astrophysics of pulsating stars and a problem of distance scale in the universe.

To conclude, I am the author and coauthor of 26 refereed papers released by the ISI Master Journal List publishers, and cited 284 times (253 without self-citations) and also of 11 non-refereed conference notes and circulars. My present Hirsch index is 10 (9th December, 2013 according to the NASA ADS database).

6. Scientific background

Eclipsing binary stars are a subclass of gravitationally bound double stars presenting periodic occultations - eclipses. In the last 15 years there has been a significant breakthrough as regards the use of eclipsing binaries as distance indicator within the Local Group of galaxies. The method based on eclipsing binaries has potential to reach 1% accuracy (Paczyński 1997). It is a limit of the systematic uncertainty of absolute flux calibrations of modern photometric systems. Distance determination to eclipsing binaries combines geometrical considerations with the scaling of observed flux at Earth. The geometrical part of considerations is common to most

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implementations of the method: the determination of the absolute system's dimension from an analysis of light curve and radial velocity curves. It results in the absolute stellar radii of both components. This part of the method is best understood and has least systematic uncertainties, at least as long as we deal with well detached eclipsing binary. Such systems have small proximity effects. Having high quality light and radial velocity curves we can expect to derive stellar radii with precision of at least 1 per cent (Anderson 1991).

The second part of the method is an estimation of a flux emitted by both stellar surfaces in some chosen regions of the electromagnetic spectrum. The flux is then compared with the flux measured at Earth and an application of the inverse square distance law gives immediately the distance to the system. Here two problems arise: 1) how to calculate the flux emitted by stars *in situ* and 2) how to estimate interstellar extinction, which is affecting the light propagation in the space? When we use eclipsing binaries as distance indicators to near galaxies we can expect two main types of useful systems. The first type contains early type short period binaries with very hot and massive stars (O and/or B spectral type). The second type comprises long period binaries with red giant or clump giant stars (G and/or K spectral types). Only the systems from these two groups are bright enough to collect the appropriate quality photometry and spectroscopy. And here because of the problem 1) the method bifurcates. In the case of early type systems the flux is estimated from model atmospheres (e.g. Guinan et al. 1998, Bonanos et al. 2011), from color-temperature calibrations (Ribas et al. 2005) or from spectral type-temperature calibrations (Hilditch et al. 2005). However, such calibrations for early type stars are very approximate and using them we cannot obtain accuracy better than 10 per cent in flux estimation. The approach based on NLTE atmosphere models seems promising, but the problem lies in the absolute calibration of such models. The reason is simple: at the moment there are no single early type stars (O and B0-1 type) with geometrical parallaxes with the precision better than 3 per cent. And only such stars would be used as safe calibrators for our atmosphere models on a level of 5-6 per cent.

When the system contains late type giants, there is an additional option. We can use a calibration between stellar surface brightness and intrinsic color index. This method was applied already in ~~70'~~ /the'70s by Popper (1974) and Lacy (1977). The used calibrations based on (V-B) and (V-R) colors. The calibration is derived from empirical measurements of angular stellar diameters by interferometry (e.g. Kervella et al. 2004, di Benedetto 2005). If we choose Johnson's V band for surface brightness and unreddened (V-K) color, we have another advantage that such calibration is very little extinction dependent. Such an improvement of the method was presented by Thompson et al. (2001) who measured distance to an eclipsing binary in globular cluster Omega Centauri. Pietrzyński et al. (2009) for the first time presented the application of this method to an extragalactic binary.

Problem 2) is a standard problem in nowadays astronomy. There are many methods for finding the value of interstellar extinction and reddening. However in case of extragalactic stars the errors of extinction determination are usually not smaller than 0.03 mag. For early type stars it corresponds to 2.0 per cent error in the flux, but for late type stars the resulting error is only 0.5 per cent.

The attention given to eclipsing binaries comes for three reasons:

a. the important part of the analysis makes use of simple geometrical considerations which are little dependent on assumptions and simplifications; because of it the systematic uncertainty, which plaques other methods of extragalactic distance determinations is much reduced;
b. for a particular system we can use at least a few different applications of the method and check model consistency on many levels of the analysis;

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c. the precision of the method allows us to determine distances to nearby galaxies with accuracy better than 3-4 per cent and subsequently to calibration of important standard candles like Cepheids, RR Lyr stars or Tip-of-RGB stars.

So far the eclipsing binaries have been used to measure distances to main Local Group galaxies. Using systems with hot stars, the distance to the Large Magellanic Cloud (Guinan et al. 1998, Fitzpatrick et al. 2002, Ribas et al. 2002, Fitzpatrick et al. 2003), to the Small Magellanic Cloud (Hilditch et al. 2005, North et al. 2010), M33 (Bonanos et al. 2006), M31 (Ribas et al. 2005)was estimated. At last, using late type systems, the distance to both Magellanic Clouds was estimated (paper: **H4**, Graczyk et al. 2013, **H5)**.

The distance to the Large Magellanic Cloud (LMC) have been a subject of debates for the last 20 years. Many methods were used to constrain precisely how far this galaxy is (Gibson 2000, Schaefer 2008, Walker 2012 and references therein). The conclusion was that every method used is dominated by a systematic error and the distance to the LMC is somewhere between 47.9 and 50.6 kpc. This uncertainty was the main source of Hubble constant H_0 determination error (Freedman et al 2001, Riess et al. 2011). Results from the paper **H5** reduce significantly this uncertainty to only 2 per cent and subsequently it is no longer the main source of error in H_0 determination.

7. Summary of post-doctoral habilitation thesis

The papers constituting the achievement focus on identification and analysis of eclipsing binary stars and also on using them as distance indicators. The analysis is performed with the Wilson-Devinney program (WD, Wilson & Devinney 1971, Wilson 1979, Wilson 1993, van Hamme & Wilson 2007). Eclipsing binaries were identified in a database of the Optical Lensing Experiment (Udalski et al. 1997, Udalski 2003, Soszyński et al. 2012). The aim of the papers is measuring the distance to Magellanic Clouds, which are important rung in the extragalactic distance scale.

1. The first step is to learn a modeling of eclipsing binary stars. There are computer models developed in the last 40 years to deal with this issue. I decided to use the WD code as it is one of the most elaborated and checked programs designed for analysis of eclipsing binaries. In the paper **H1** I presented the results of my work on several systems of the Small Magellanic Cloud (SMC). The stars were found to be eclipsing binaries by the OGLE Consortium (Udalski et al. 1998). There were three main aims of this paper:

a. acquisition of the proficiency in using the Wilson-Devinney code;
b. determination of the physical parameters of several hot and massive stars in the SMC; I hoped that it would be the first such work for a number of stars in the SMC, however Harries et al. (2003) outgo my paper slightly.
c. selection of the best systems for distance determination to the SMC.

Paper **H1** was devoted mostly to massive early type systems. The reason for it was that I was impressed by a series of papers published by Guinan and his collaborators. These papers suggested that such systems are indeed the most suitable for distance determination. The correspondence with prof. Bohdan Paczyński made me change my mind and I began looking for another implementation of the method. It led me to the discovery that late type systems containing giant stars are optimal for the purpose of distance determination. I have prepared a short list of such systems in LMC with a help of an eclipsing binary catalog by Wyrzykowski et al. (2003). Few years later due to collaboration with dr hab. Grzegorz Pietrzyński we managed to publish distance determination to the first binary from the list OGLE-051019.64-685812.3 (Pietrzyński et al. 2009).

2. Paper **H2** presents new method of identification of eclipsing binaries in large photometric surveys like the OGLE. The method is optimized for the identification of detached eclipsing binaries because such systems are most suitable for distance determination (Paczyński 1997). It

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exploits some statistical properties of brightness distribution like the skewness and the curtosis. Methods used before usually utilized the Fourier Transform for period finding and they were most efficient in detecting close binaries with short orbital periods. A test of the method performed on the OGLE-II database was positive: all eclipsing binaries from the catalogue by Wyrzykowski et al. (2004) and additionally about 25 per cent of new eclipsing binary stars were found. These new identifications were mostly well detached systems with short eclipses and eccentric orbits.

3. The method presented in paper **H2** was successfully used to build a new catalog of eclipsing binaries in the LMC. The new catalog is based on photometric data from the third part of the OGLE project and it is the largest catalog of eclipsing binaries published to date. The way it was prepared and its statistical properties are described in paper **H3**. The detached eclipsing binaries constitute 62 per cent of all items in the catalog. This result is almost identical with a frequency of detached eclipsing binaries estimated from the *Kepler* space mission (Prsa et al. 2011, Slawson et al. 2011). A curious result was the detection of many eclipsing binaries showing transient eclipses i.e. eclipses were appearing and then disappearing. The reason for the phenomena is probably a precession of their orbital planes induced by a third body gravitational force. Another important result was the detection of a number of detached, late type eclipsing binaries with giant components. These systems make a core of the sample we used to precisely determine the distance to the LMC (paper **H5**).

4. The analysis of an eclipsing binary OGLE SMC113.3 4007 lying in the SMC was presented in paper **H4**. The system was selected as a very good exemplary to show how our method worked. What makes it perfect? This binary has a few attributes which minimize the systematic uncertainty of its distance determination:

a. it is a double-lined spectroscopic binary
b. it is relatively bright (V < 17 mag)
c. it is a well detached system
d. components of the system are non-active and photometrically stable stars
e. it has deep eclipses
f. both stars are of similar surface temperature.

Point f) needs some explanation. The atmosphere models are used to extrapolate the components' light ratio from the optical to the infrared region of the spectrum. Subsequently such light ratio is used to calculate (V-K) color index of both stars of the system. The (V-K) color is then used to calculate the distance using calibration of di Benedetto (2005). Extrapolation is forced by the lack of light curve in K-band, which could be used to calculate the light ratio directly.

5. Paper **H5** presents a summary of our effort to measure the distance to the LMC. The resulted distance of 49.7 +/- 1.1 kps is the most accurate of distances to this galaxy published up to date and has the lowest systematic uncertainty. The high precision of our results makes it important for comparison with future distance determinations to the LMC, especially much anticipated result from the GAIA mission. In the Supplementary Information, there are details of the method. The way we derive distance to a particular system was improved, in respect to the method presented in paper **H4**, by inclusion of the analysis of atmospheric parameters based on disentangled spectra of both components. Such additional analysis allows us to independently derive temperatures and metallicity of stars. It is important for two reasons: 1) we find proper temperature scale of the system and 2) we obtain supporting information about reddening in the direction of a particular star. Another improvement presented in paper **H5** is the implementation of Monte Carlo simulations to verify statistical uncertainties in the derived physical parameters of stars and distances.

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8. Remaining important post-doctoral scientific achievements

- determination of astrophysical parameters of eclipsing binary containing classical fundamental Cepheid OGLE-LMC-CEP-0227 (Pietrzyński et al. 2010), it is the first precise determination of Cepheid's dynamical mass (with accuracy better than 2 per cent);
- determination of astrophysical parameters of an unique eclipsing binary containing a pulsating star mimicking a RR Lyr star, however the pulsating component has quite different evolutionary status than RR Lyr stars (Pietrzyński et al. 2012);
- elaboration of a new method for analyzing light curves of eclipsing binaries containing radially pulsating star; method application to a case of Cepheid OGLE-LMC-CEP-0227 (Pilecki et al. 2013) and determination of the projection factor; the projection factor is important for Baade-Wesselink type methods of distance determination to cepheids.

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