HABILITATION SUMMARY

1. Name: **Marcin Kiraga**

2. List of all scientific degrees: (including name, place, and the date of obtaining, provide the PhD thesis title)

Master of Science (MSc) , physics (specialty: astrophysics), Physics Department of Warsaw University, September 1993, MSc thesis: "Gravitational microlensing due to Galactic disk stars"

Doctor of Philosophy (PhD) , physics (specialty: astrophysics), Physics Department of Warsaw University, June 2000, PhD thesis: "Hydrodynamical simulations of convection zone and its influence on the lower stable layer", supervisor prof. dr hab. Kazimierz Stępień

3. Employment:

Oct 1993 - Sep 1998 - PhD student, Physics Department of Warsaw University (Astronomical Observatory)

Mar 1999 - Dec 1999 - technical position, Physics Department of Warsaw University (Astronomical Observatory)

Oct 2000 - Feb 2001 - jr. specialist, Physics Department of Warsaw University (Astronomical Observatory)

Feb 2001 - present - assistant professor, Physics Department of Warsaw University (Astronomical Observatory)

4. Habilitation achievement
(a) title:

Photometric variability of stars coincident with X-ray sources

(b) author(s), title(s) of publications, year of publishing, journal name:

H1. Kiraga, M., Stępień, K., "Age–Rotation–Activity Relations for M Dwarf Stars Based on ASAS Photometric Data", 2007, Acta Astronomica, 57, 149

H2. Kiraga, M., "ASAS Photometry of ROSAT Sources. I. Periodic Variable Stars Coincident with Bright Sources from the ROSAT All Sky Survey", 2012, Acta Astronomica, 62, 67

H3. Kiraga, M., Stępień, K., "ASAS Photometry of ROSAT Sources. II. New Variables from the ASAS North Survey", 2013, Acta Astronomica, 63, 53

Marcin Kiraga

Introduction

The X-ray emission usually points to interesting astrophysical phenomena related to hot plasma, high energy particles and magnetic fields. Several different stellar X-ray sources are known. The brightest ones are binaries with mass transfer from a star to a black hole or neutron star occurring via stellar wind or the inner Lagrange point. The X-ray emission is also detected from single neutron stars, cataclysmic binaries (mainly from the boundary layer close to the surface of white dwarf), hot white dwarfs, hot and luminous O and B stars, where the X-ray emission is related to shock waves due to instabilities in stellar winds or due to colliding stellar winds in close binary systems. However, the most ubiquitous stellar X-ray sources are stars with sub-photospheric convective layers, resulting in magnetic activity and presence of hot, (multi-million Kelvin) coronae. The power of coronal X-ray emission strongly depends on rotation rate and the stellar type but for most active stars is at the level of 10^{-3} bolometric luminosity. There are many unsolved (or not fully solved) problems related to stellar magnetic activity, for example magnetic field generation via dynamo action, not fully described even for the Sun, magnetic activity cycle, angular momentum loses via magnetized stellar winds (magnetic breaking) and related activity - rotation rate relation and its dependence on time. Rotation is one of the most important parameters governing stellar magnetic activity. It is also very important for problems related to stellar interior structure and evolution. Photometric variability due to rotation of stellar nonuniform brightness surface is relatively simple and direct measure of rotation period. Coronally active stars are good candidates for photometric period study due to presence of spots, regions where strong magnetic fields diminish convective transport. The properties of solar spots are quite discouraging: they are quite small (photometric variability rarely exceeding 1%), relatively short living (their lifetime is comparable to solar rotation period), and they occur preferentially in the maximum of activity cycle (periods with no prominent spots may last for years). Starspots dimension may vary and they could be subject of differential rotation due to placement at different astro latitudes (resulting rotation period for given star may vary). However, there are many stars much more active than the Sun with much higher level of chromospheric and coronal emission and larger starspots. These are usually young fast rotating stars or close binary systems with forced tidal synchronization of orbital and rotation periods. The starspots on active stars placed above the main sequence (both young T Tauri stars and old stars in binary systems) may result in brightness changes in excess of 0.5 mag (Strassmeier 2009). The variability of main sequence stars due to presence of starspots is smaller due to larger pressure at the photospheric level, so the area where dynamics of ionized gas is dominated by magnetic field is smaller than for larger stars.

The first paper (H1) presented as scientific achievement presents detection of rotation periods for 31 M dwarf stars using ASAS-3 photometric data (Pojmański 2002), analysis of their rotation - activity - age relation and first estimation of empirical convective turnover times for such stars. Two following papers (H2 and H3) present catalogs of variable stars related to bright X-ray sources from ROSAT all-sky survey (RBSC - ROSAT Bright Source Catalog - Voges et al. 1999) found with ASAS-3 (H2) and ASAS-3N (H3) photometric data. There are 2302 stars in the first catalog (half of them are new variables) and 307 stars in the second (mostly new variables). These catalogs contain data useful for study coronal activity - rotation relation for several classes of active stars.

Photometric variability of neighboring M-dwarf stars (paper H1)

M-dwarf stars, with masses from 0.1 to 0.6 solar masses, are the most ubiquitous stars in our neighborhood (about 70% of components in 100 closest stellar systems). First detections of rotation periods for M-dwarfs have been published in the sixties of the previous century (e.g. Krzemiński 1969), but before 2007 there was a small number of such stars with known rotation periods, especially with periods larger than ten days related with lower level of activity.

The X-ray flux data were taken from Hünsh et al. (1999) and NEXXUS2 database (Schmitt and Liefke 2004). From these databases we selected 180 M stars with declination smaller than +28 deg, and mean V magnitude larger than 8 and smaller than 12.5. Many late type stars show flare activity related to magnetic field reconfiguration. These events may result in unpredictable and, in the case of M-dwarfs, significant brightening of the star. Photometric points with large deviations from the mean value have large weights in period searching algorithms, so we decided to eliminate photometric points with difference from mean value larger than 3.5 standard deviations. Late type stars also show season-to season light variations which are usually interpreted as resulting from activity cycles, so the photometric data from individual seasons with at least 50 useful observations have been analyzed separately. A period search was also performed for all data points after eliminating season to season variations. We used AoV algorithm (Schwarzenberg-Czerny 1989), and when AoV statistics was larger than 8 for particular season or for the whole data set we considered the star as suspected variable and checked its photometric data visually. Finally we obtained 31 stars with periodic variability and classified them as spotted rotators. Variability amplitudes even for very active stars were below $\Delta V = 0.05mag$, with the exception of GJ 103 with variability amplitude of $\Delta V = 0.06mag$. In our analysis we included photometric periods taken from literature for GJ 411 (Noyes et al. 1984) and GJ 699 (Benedict et al. 1998).

The Rossby number is the ratio of rotation period to the convective turnover time close to the bottom of convective zone and is often used in problems related to stellar activity. The rotation period could be obtained from photometry, but for the estimation of convective turnover time models of stellar interior are necessary. It is also possible to obtain the empirical turnover time as a parameter in rotation period - level of activity relation, using the calibration obtained by Stępień (1994). Convective turnover time should depend on mass so we divided our star sample into four mass intervals (0.11-0.20, 0.33-0.39, 0.43-0.52 and 0.56-0.65 solar masses) using mass - absolute luminosity (V band) relation (Delfosse et al. 2000). Bolometric luminosity (L_{bol}) was obtained using bolometric corrections given by Delfosse et al. (1998) and Petersen (1983). We fitted linear relation between $\log (L_X/L_{bol})$ and rotation period for stars in every mass bin and mean empirical turnover times for different masses were obtained. The empirical turnover time was for the first time obtained for M-dwarf stars due to detection of more than 10 rotation periods longer than ten days. The empirical turnover time is longer for less massive stars, as was expected.

The full kinematical data were known for 27 stars from our sample (including GJ 411 and GJ 699) and 20 of them were classified as young disc stars, one (GJ 2036A) as young disc/old disc object, and six as old disc stars (GJ 699 is sometimes referred as a halo star). The very active star GJ 2036A also belongs kinematically to the young disc due to new radial velocity measurement. All old disc M-dwars have rotation periods longer than 30 days and $R_X = \log (L_X/L_{bol})$ below -4.4. The difference in activity level R_X between active M dwarfs (age about 1 Gyr) and stars of old disk (age about 10 Gyr) is about 1.7 dex. This result confirms conclusions from earlier studies (e.g. Feigelson et al. 2004, Silvestri et al. 2005) that stellar activity drops faster with age than $L_X \sim t^{-1}$ resulting from the well known power law dependencies for main sequence stars of given mass: $v_{rot} \sim t^{-1/2}$ (Skumanich 1972) and

$L_X \sim v_{rot}^2$ (Pallavicini et al. 1981, Pizzolato et al. 2003).

Photometric variability of stars related to the bright X-ray sources based on ASAS-3 photometry (paper H2)

We found ASAS data very useful to study low amplitude variability related to rotation. The X-ray data was taken from RBSC (Voges et al. 1999). This catalog includes 18811 sources with count rate more than 0.05 cts/s, with at least 15 photon counts. There are 13793 entries from RBSC south of declination +29 deg, the area covered by ASAS-3 observations. The optical identification of the X-ray sources was based on ROSAT coordinates and the search in ASAS photometric database was performed within 30" around given position. The initial period search was performed for photometric data sets with following properties: (i) number of data points was not less than 40, (ii) the mean *I*- or *V*-band magnitude was between 8 and 12.5, (iii) for stars brighter than 8 mag dispersion was less than or equal to 0.1 mag.

We treated V and I band data separately and initial period search was performed for 5851 sources in the *I*-band and and 4207 sources in the *V*-band (altogether 6026 stars) using the AoV algorithm in similar way as in paper H1: rejection of outlying points, analysis of particular seasons (with at least 40 observations), analysis of the whole data set after correction of season to season variations. For almost 3000 stars AoV statistics was larger than 10 (using 6 phase bins); these stars were further investigated using CLEAN algorithm (Roberts et al. 1987), and their photometric data were inspected visually. Finally we obtained a list of 2302 objects with detected periodic variability. For periodic stars we looked via SIMBAD database for additional information helpful for star classification or confirmation of obtained period (e.g. information on projected $v \sin i$ may be useful for elimination of possible aliases). The catalog includes summary of photometric properties (number of observations, mean magnitudes and their dispersions, variability period and its amplitude), basic RBSC data (number of counts per second, "color" - the ratio of the difference between "hard" and "soft" photon counts to all counts), and the value of $\log{(L_X/L_{bol})}$. Bolometric correction was calculated from mean *V-I* color and using fit to atmospheric models presented by Bessel et al. (1998). The catalog includes also following data from SIMBAD database and literature (if available): object name and type, proper motion, heliocentric parallax, radial velocity, projected rotational velocity, equivalent width of the lithium line, spectral type, known close neighbors (both photometric and spectroscopic).

Periods for almost half of the stars listed in the catalog had been known before, but the data collected from literature allowed in many cases for better star classification.

Spectral classification available for 1699 stars indicates that most of them are related to X-ray sources of coronal origin (1669 stars have spectral types from M to F). For a few hot O and B type eclipsing stars X-rays may be related to wind collision or other phenomena occurring in close binary systems. There are at least 11 white dwarfs and six of them are components of cataclysmic systems. Optical counterpart of hard X-ray and gamma source IGR J16194-2819 is a red giant presenting (most probably) ellipsoidal variability with a period of 193 days, orbiting neutron star. This system is an example of a symbiotic X-ray binary with high energy emission related to the compact object. Among stars with known luminosity class most are on main sequence (734), but subgiants and giants are also quite numerous. Photometric variability is related mainly to rotation of spotted surface (1936 stars) and eclipses in binary systems (347 objects).

The catalog includes some object worth particular attention. The best known examples of high amplitude variability due to presence of spots are pre-main sequence V410 Tau and evolved XX Tri with ΔV up to 0.65 mag (Strassmeier 2009). The star ASAS 063656-0521.0 presents particularly large brightness variations due to presence of spots (up to ΔV= 0.8 mag). This star has period 5.029 days and its very high activity ($\log(L_X/L_{bol})$ = -2.7) is most probably related to presence of a close companion. During ASAS observations the variability amplitude increases from initial modest $\Delta V \approx 0.2$ mag, while mean brightness of the star decreases (see fig. 1).

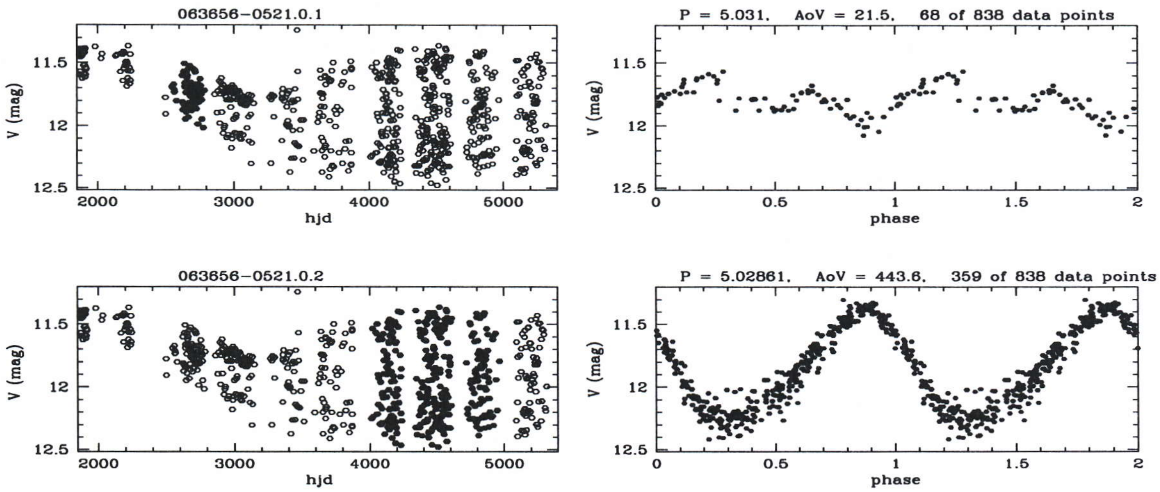

Figure 1: Star ASAS 063656-0521.0 presents large changes in spot coverage. *Left side:* V - band photometric data as a function of hjd = HJD - 2450000 d. *Right side:* phased light curve at the time of modest (upper panel: hjd between 2545 and 2785 d) and very high variability (lower panel: hjd between 4014 and 4967 d).

Two cataclysmic variables (V341 Ara, IX Vel) present non typical brightness variations with periods 10.0 and 17.7 d, respectively. All photometric data of these stars present large scatter, but we were unable to fit any period longer than 0.1 d to the most of data. Periodic modulation of the main brightness was present during only one season, for both stars. Variability of V341 Ara with similar timescale has already been reported (14 d - Berdnikov and Szabados 1998, 11 d - Hipparcos photometry - Perryman et al. 1997) and its amplitude was so large that the star was classified as population II cepheid. Orbital period of IX Vel is equal to $P_{orb} = 0.193929$ d (Beuermann and Thomas 1990), so variability on timescale of ten days may be related to disc phenomena like changes in accretion rate, precession, changes in viscosity.

Photometric variability of stars related to the bright X-ray sources based on ASAS-3N photometry (paper H3)

ASAS-3 cameras located at Las Campanas provided photometric data for stars with declination smaller than 29 deg.

ASAS project had all sky coverage since installation of ASAS-3N cameras on Maui, Hawaii ($\varphi = 20.707^o$; http://www.astrouw.edu.pl/asas/). ASAS-3N obtain useful photometric data for stars fainter than ASAS-3 at Las Campanas due to larger aperture and the same exposure time. Optical counterparts to X-ray sources from RBSC with declination larger than –25 deg (12910 sources) were searched using ASAS-3N database within 30" from ROSAT position. Initial period search was performed for stars with mean V magnitude between 8.0 and 14.0, and at least 40 observations (4324 objects) in a similar manner as in

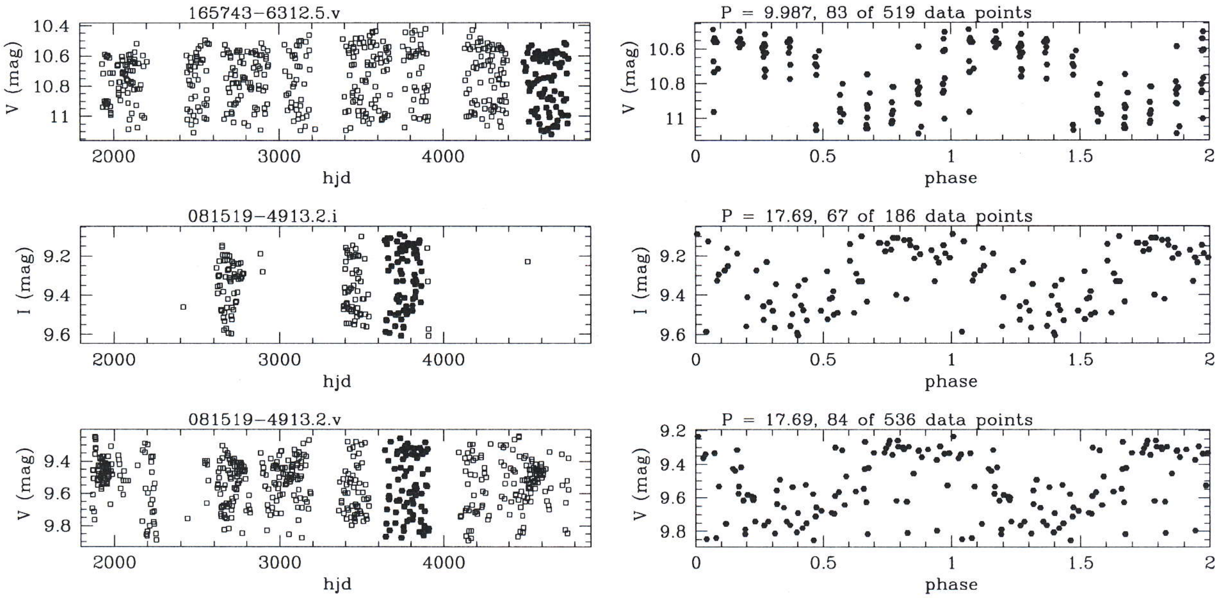

Figure 2: Photometric data for two cataclysmic binaries V341 Ara and IX Vel. Photometric data points as a function of hjd = HJD − 2450000 are presented on the *left side*. Phased light curve of data showing periodic variability is presented on the *right side*. *V*-band data for V341 Ara is presented in the *upper panels*, *I*-band and *V*-band data for IX Vel are presented in the *middle panels* and *lowermost panels*, respectively. Periodic variations for both stars were possible to obtain only during single season (marked with full dots on the left panels).

the paper H2. (rejection of outlying points, analysis of particular seasons, and analysis of a whole data set). The AoV statistics was higher than 10 for 1603 stars, of which 647 have been already listed in catalog presented in paper H2, so we decided to concentrate on new variables. Finally, the catalog includes 307 periodic variable stars, mostly new, with period determination for six previously known variables and new period determination for seven stars.

So far, only V-band ASAS-3N photometric data are available. The V-J color was used for calculation of bolometric correction based on calibration given by Casagrande at al. (2008, 2010). The J band magnitudes and information about neighboring stars were provided by 2MASS data (Skrutskie et al. 2006). The catalog includes information about photometry (ASAS V-band, 2MASS - J-band), blending in 2MASS data, variability (period, amplitude) and log (L_X/L_{bol}). Additional data from the SIMBAD database and literature like parallax, radial velocity, projected rotational velocity, presence of lithium line are given only for few stars (e.g. $v \sin i$ was available for 17 stars, and heliocentric parallax was found for 15 stars). Spectral type is given for 136 stars with 2 A-type stars and other belonging to spectral types from M to F. Coronal activity is the most probable source of X-ray emission for these stars.

Summary

Papers presented as the scientific achievement significantly increase the number of stars with known both the X-ray flux and the variability period. The paper H1 presents 31 rotation periods (21 new) found for M-dwarf stars with known X-ray fluxes using ASAS-3 photometric data, and subsequent analysis of period - activity relation. The new rotation periods longer than 10 days allowed to estimate empirical convective turnover time for M-dwarfs in four mass intervals. Kinematically selected old disc stars have long rotation periods and low activity. Activity appears to decrease faster with time than predicted by Skumanich law and most popular period - activity relation.

Catalogs presented in papers H2 and H3 are very useful in analysis of problems related to stellar activity. They include more than 2600 stars with known variability period and the X-ray flux (more than half of them are new variables) and most of them are coronally active. The relation between $\log(L_X/L_{bol})$ and logarithm of the period expressed in days ($\log(P)$) is presented in Fig. 3. On the left side of Fig. 3 there are all stars included in catalogs H2 and H3, whereas on the right side we present stars classified as spotted rotators. Data included in the catalog enable selection of several classes of active stars (pre main sequence stars, main sequence stars, evolved stars, single stars, close binaries). For example, Wright et al. (2011) in a recent analysis of period - coronal activity relation for main sequence stars, used the data for 824 stars found in literature. There are at least 750 main sequence stars in catalogs H2 and H3 and only 41 of them have been included in Wright el al. (2011) analysis. Next study of period - activity relation may include additional several hundreds of main sequence stars.

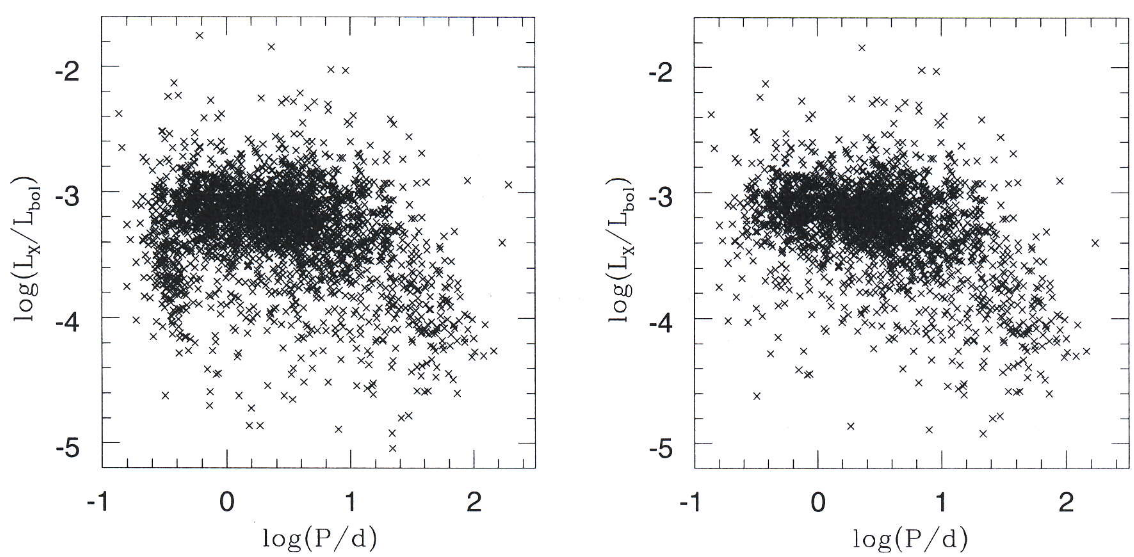

Figure 3: The dependence of X-ray activity level ($\log(L_X/L_{bol})$) on the logarithm of the rotation period, expressed in days ($\log(P)$) for stars included in catalogs described in papers H2 and H3. *Left side:* all stars, *right side:* stars classified as spotted rotators.

There are few non-coronal X-ray sources in catalogs presented in papers H2 and H3, some of them particularly interesting. Red giant GSC 06806-00016 (ASAS 161933-2807.5) is an optical counterpart to the X-ray and gamma ray source IGR J16194-2810 and it displays the photometric variability with a period of 193 d interpreted as the result of ellipsoidal distortion (we consider pulsations with a period of 96 d as less likely). This star is classified as symbiotic X-ray binary. Cataclysmic binaries V341 Ara, and IX show modulations of the mean brightness with a timescale of ten days with unknown origin, but most probably related to changes in the accretion disc.

5. Presentation of the remaining scientific achievements.

I was born 18.09.1969 in Warsaw. I'm married and we have four children.

I begin astronomical studies at Physics Department of Warsaw University in Oct 1988. My MSc thesis, written under supervision of prof. Michał Jaroszyński, was finished in Sep 1993 and was related to gravitational microlensing and galactic structure. The first studies of gravitational microlensing towards Galactic bulge consider only disk stars acting as lenses and neglected self lensing of bulge stars (Paczyński 1991). The contribution of bulge lenses has been calculated by Greist et al. (1991), but due to artificial cut off of bulge star distribution at 8 kpc the resulting optical depth to gravitational microlensing ($\sim 10^{-7}$) was much smaller than for disk star lenses ($\sim 4 \cdot 10^{-7}$) and the number of microlensing events has been underestimated. The correct calculation of gravitational microlensing events rate towards the Baade Window (the main target of the first phase of the OGLE survey: $l = -1^o$, $b = -4^o$) for axi-symmetric bulge model has been presented by Kiraga and Paczyński (1994). The expected optical depth for microlensing due to known stellar populations was calculated to be $0.85 \cdot 10^{-6}$. Roughly half of this value was expected for disk star lenses. Actually, the optical depth to gravitational microlensing towards Baade Window is significantly (about 2-3 times) larger due to the presence of Galactic bar with a major semi-axis pointed towards us.

I have spent a month as an intern at the Astrophysical Science Department of Princeton University under supervision of Professor Bohdan Paczyński (April 1996). The main goal of the visit was to analyze distribution of Galactic disk stars towards the Baade Window using the color - magnitude diagrams (CMD) obtained by OGLE. The presence of narrow band of stars on the CMD was interpreted by Paczyński et al (1994) as evidence for a large number of disk stars out to distance about 2 kpc and a hole in the disk at larger distances. However, the narrow band of stars appeared to include turn-off point stars shifted in color by interstellar extinction and the resulting distribution of disk stars may be interpreted as constant (Kiraga et al. 1997).

In October 1993, I started my PhD studies at Physical Department of Warsaw University under supervision of Prof. Kazimierz Stępień. The main subject of my PhD thesis was related to hydrodynamical simulations of convection and its influence on neighboring stable layers (due to thermal penetration, mixing of elements, excitation and propagation of internal gravity waves). From Sep 1996 to Jun 1997 and from Feb 1998 to Oct 1998 I visited Paris Observatory, section Meudon, and worked under supervision of Prof. Jean-Paul Zahn. I defended my PhD thesis in June 2000. In September 2001, I participated in the summer school held in Potsdam devoted to numerical modeling of turbulence, and in November 2001 I was invited by Prof. Axell Brandenburg to one week visit at NORDITA in Copenhagen.

Internal gravity waves (IGW) excited by convection and propagating in the stable layers are considered as important for transport of energy, angular momentum and have possible contribution to mixing of matter (e.g. Press 1991, Schatzman 1996, Kumar et al. 1999). The detailed properties of IGW are described in these papers, but their importance for fore mentioned processes depend on their amplitude and spectrum. The dynamics of the lower part of solar and stellar convection zones remains unknown. The most popular mixing length theory (MLT) assumes dimension of large scale vortexes equal roughly to pressure scale height and their velocities should be about $0.1(F_C/\rho)^{1/3}$ (F_C - convective flux, ρ - gas density). Other models, like inspired by numerical simulations, convective plume model (Rieutord and Zahn 1995) predict smaller scale turbulent motions and larger velocities when compare with MLT. The presence of IGW has been noticed in several hydrodynamical simulations (e.g. Hurlburt et al. 1994, Brummell et al. 2002), but the published periodograms have been dominated by standing waves, so the resulting flux of energy carried by the waves could not be computed. The spectral properties and the flux of energy carried by IGW were presented by Kiraga et al. (2003). The lengths and the periods of waves with largest amplitude corresponds to large scale convective motions, they are smaller than in MLT but larger than in convective plume model.

The main subjects of my latter work are rotation - coronal activity relation for M-dwarf stars and use of ASAS data for study of photometric variability of active stars. The resulting scientific papers are presented as the scientific achievement.

Marcin Kiraga

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