Final report on the activities of Dr Talat Akhunov during the period 14 May 2012 – 15 November 2013 in the AEOS group at the Institute of Astrophysics & Geophysics, Liège University

Image processing in general, as well as obtaining photometric and astrometric data in particular, plays an important role in astrophysics, enabling astronomers to study the physical properties of various classes of celestial objects. In parallel to the development of observational technology, it is thus necessary to set up highly performing methods and programs for all the steps of image processing: subtraction of the bias and dark current, flat field correction, astrometric calibration, photometric measurements and calibration and others.

The AEOS group from the Astrophysics & Geophysics Institute (Liège University) is involved in running such developments. In particular, I have integrated the team to prepare the data reduction and calibration of observations to be obtained with the 4m International Liquid Mirror Telescope - ILMT that is presently under construction at Devasthal, India. This telescope is designed to record deep images of the sky over a range of 24h in right ascension and 27’ in declination. The main aim of this project is to get accurate photometry of variable objects, including multiply imaged quasars. Accordingly, there is also a need for very efficient methods and computer programs to reduce and analyse the photometric images.

The first step to contribute to this objective has been to analyse a preliminary data set obtained with a 14” telescope at the Observatory of Calern (France) and with a 1.3 m telescope at the Devasthal observatory (India). These data sets were obtained in the Time Delay Integration mode, alike the images that will be soon obtained with the 4-m ILMT.

With the 14” Calern telescope, eight direct CCD images have been obtained: 3 in the **g** band, 2 in **r** & 3 in **i**, all in the TDI mode with the SBIG STL4020 CCD camera. Our task was to find the best way of calibrating photometrically these data sets, i.e. to transform the instrumental magnitudes **g'**, **r'**, **i'** into the **g**, **r** & **i** SDSS standard magnitudes. For this purpose, we have proceeded as follows:

- All CCD images were linearly translated into the same coordinate system because the same objects had different coordinates on the different images. A maximal shift of up to ~270 pixels in the Y (Dec) direction and ~ 1000 pixels in the X (RA) direction was applied in some cases;

- We then determined the coordinates of all the objects on the CCD frames using the Sextractor program. The detector sensitivity depends on the pass band. Therefore, on different images we got different numbers of detected objects – about 200 objects in **i**, ~ 350 in **g** and ~ 440 in **r**;

- We chose the longest list to perform aperture photometry (**phot** task in IRAF/DAOPHOT). As a result, we were able to derive the instrumental magnitudes **g', r', i'** for all the objects, with their error bars. To convert them into the SDSS **gri** system, we chose some reference stars and their **g, r, i** magnitudes from the SDSS-DR7 database (aladin.u-strasbg.fr/java/nph-aladin.pl?frame=downloading; Abazajian K., Adelman-McCarthy J.K., et al. ApJS, 2009, **182**, 543). After, we used 3 models to convert the **g'r'i'** magnitudes into the **gri** system, adopting the new notations **g" r" i"**: a) a model with colour, magnitude dependence + constant term; b) a model with only a constant term; c) a model with magnitude dependence + constant term. Here we used three types of unknown coefficients - **α** and **a** which are responsible for colour and magnitude dependencies respectively, and **b** is a constant term. To calculate these coefficients, a program has been developed to derive the weighted average values of the instrumental magnitudes, their error bars as a cubic function of the DR7 mag. After that the program provides the values of the **α**, **a** and **b** coefficients, using the minimum least squares method. In addition to those derived coefficients, the program also returns the new converted **r" g" i"** magnitudes for the reference stars and all objects, separately. And as usually, we used the criteria (**r" – r)** -> 0**, (g" – g)** -> 0 **and (i" – i)** -> 0**.**

Further analysis showed us that we can use the simplest models for the cases of the **g** and **r** pass bands. No colour or magnitude dependence was found in the magnitude transformation for the **g** and **r** pass bands. But a slight magnitude dependence may occur for the case of the **i** filter.

Another part of the database has been obtained on 2-7 June, 2013 with the 1.3 m telescope at the Devasthal observatory in the TDI mode with the same camera as at the Calern Observatory. During this observing complain 88 optical frames have been obtained, covering the part of the sky from ~14h up to ~21h in RA. The procedures of the treatment of these frames consist of several steps:

dark current subtraction, flat field correction, sky subtraction, astrometric calibration, photometric measurements and calibration. The methodology and programs for the bias and dark subtraction, flat field correction, as well as cosmic ray correction were developed by Ludovic Delchambre. The next step consisted in the sky subtraction. Analysis of the frames showed that their background has a systematic tendency to change along the declination axis and right ascension (time). This problem was resolved with the help of original step-by-step technique, proposed by prof. J. Surdej. In this method the sky background has been decomposed into two main components, one along the vertical axis and one along the horizontal one, respectively. We used median filtration with a binning width of 30 pixels and a bad pixel mask to fit these components and to get average background masks which were simply subtracted from the original frames.

The next step was the astrometric calibration of the frames, i.e. we had to find the exact positions of the frame centres and of the objects. To do this we decided to use the standard WCSTOOL package program which led us to solutions with equatorial coordinates for the J2000 equinox. It was found that there was a sinusoidal dependence between the declination (DEC) of the field centres and the time (or RA), although our observations were precisely made at the zenith. Therefore, we did not expect any change of the declination. This effect disappeared after properly taking into account the precession + nutation of the Earth.

All these works have been performed in collaboration with our colleagues from the Poznan Astronomical Institute of the Adam Mickiewicz University. They provided access to a computer cluster in order to store the database and to carry out fast calculations. In August 2013, during 1 week, I visited the Poznan University. During my visit to Poznan, I, Prof. J. Surdej and Dr. P. Bartczak (leader of the Poznan group) have discussed in depth all problems related to the treatment and processing of TDI CCD frames. They concern the subtraction of the sky background, the astrometric calibration, and the optimisation of various software programs.

To render the image processing more clear and efficient, Dr. P. Bartczak has proposed to render their computing cluster accessible to distant members of the ILMT project. For this, we have designed appropriate scripts, and they were successfully tested on local computers and later, on the computers of the Liége University.

With regard to the sky background subtraction, several procedures have been designed which take into account different aspects of the sky background: they allow to represent the sky background as a very smooth polynomial function or in the form of a sliding average. They also lead to the construction of bad pixel masks in order to be aware about the possible contamination due to bright objects and the halos around them.

We are working on the problem of automating the calibration tool to transform the instrumental photometric magnitudes into standard ones (SDSS system).

On the other hand, we have decided to apply a new and promising technique to retrieve the photometry of all lensed images constituting a gravitational lens system. The photometric analysis of lensed quasar images may help researchers not only to better understand the physical nature of the lensed source but also of the lens itself and the Universe as a whole. This new photometric method has first been applied to the CCD frames of H1413+117. They were acquired during the 2002 - 2008 period at the Maidanak observatory (Uzbekistan).

H1413+117 is a famous gravitational lens system, which along with the Q2237+0305 quadruply imaged quasar, is promising in terms of the study of micro-lensing effects. First, the redshift of the H1413+117 quasar-source is known (Zq = 2.55), and it was subsequently found to be a four-component system with angular separations of order of 1 arcsecond (P. Magain, J. Surdej, et al., Nature, 1988, 334, 325-327). During the past years, observations of the system were made in different wavelength ranges. Abnormal flux ratios in different parts of the spectrum showed several evidences of micro-lensing for the D component.

To derive the magnitudes of the lensed QSO images, we have developed a new photometric technique – the adaptive PSF fitting technique. First, this method only works with a numerical *PSF* and does not require an analytical representation. Secondly, there is no need for the assumption of the *PSF* invariance over large regions of the CCD frame. To calculate the fluxes of the lensed components, we assumed the *PSF* invariance over only the GLS (i.e. less than 2 arc sec). The problem of deriving the fluxes of the lensed QSO images is reduced to solving a system of ordinary linear equations. The shape and width of the light distribution of the *PSF* does not really matter. Probably, our method can also be successfully used for the case of defocused images.

As a result of applying the adaptive PSF fitting method to the Maidanak H1413+177 dataset, we provided new long-term light curves of the lensed images. To determine the photometric error bars affecting each data point, we simulated for each of these 500 frames including all the key factors: the Poisson noise due to the GLS, white noise for the sky background, uncertainties of the lensed image centring at the sub-pixel level, etc. The measurement of the magnitude uncertainties of the lensed components corresponds to the standard deviation of the distribution of the results obtained for the simulated frames.

We distinguished the light curves of the Clover Leaf lensed components in the *V* and *R* filters, and the *V* - *R* colour curve. The light curves of the whole system and of the individual components correlate very well with each other. We see two types of variations: short-term (with amplitude ~ 0.1 mag) during separate seasons and long-term (with amplitude larger than 0.15 mag) over the time scale of several seasons. The colour changes are also characteristic of quasars (as in UM673, see Koptelova et al., A&A, 2012, 544, id. A51, 2011) – with an apparent flux decrease leading to some reddening, and vice versa – during an apparent flux increase, the system becomes bluer.

Our long-term light curves allowed us to calculate the time delays between the lensed images of the Clover Leaf. In the calculations, we separately relied on the seasons between 2003 and 2006 showing the most frequently sampled data. We did not use the whole light curves because of gaps between seasons with durations of several months. On the other hand, micro-lensing events may change the magnitude difference between the components (this in turn makes it impossible to use the light curves of the components in a general way).

This problem was solved with the help of different methods and approaches: we used chi-squared tests with linear interpolation and two dispersion methods. To estimate the errors of our time delay predictions and their confidence levels, we generated synthetic light curves on the basis of previously calculated magnitudes from simulated CCD frames. As a second alternative method, we used the classical method of normal distribution of the stellar magnitudes. Also, we considered separately the direct light curves and median filtered light curves.

Fortunately, thanks to a significant decrease in flux of all the components in 2004 (JD = 2453130 ÷ 2453150), we could obtain some relevant values for the time delays. Our values are fully consistent with the independent results obtained by (Goicoechea & Shalyapin, AJ, 2010, 708, 995).

The complex and sometimes uncorrelated behaviours of the light and colour curves indicate some active internal variability and continuous influence of micro-lensing. The micro-lensing rate measured for the *A*, *B*, *C* components, on average, corresponds to the characteristic rate of micro-lensing ~10^{-4} mag/day from other known gravitationally lensed quasars (Gaynullina et al., A&A, 2005, 440, 53; Vakulik et al., A&A, 2006, 447, 905; Goicoechea & Shalyapin, AJ, 2010, 708, 995; Tsvetkova et al., MNRAS, 2010, 406, 2764; Ricci et al., A&A, 2011, 528, id. A42, 8 pp.).

However, we found an unusually strong influence of micro-lensing in the D component. In 2004, the light of this component has varied with a rate of $\sim 10^{-3}$ mag/day and almost reached the brightness of the C component in 2005. We can assert that this is a recurrent process, as similar flux variations have been previously reported (Remy et al., 1996; Arnould et al., 1993).

Even more dramatic brightness changes of the lensed components due to micro-lensing have been reported for Q2237+0305 (Koptelova et al., 2007; Udalski et al., 2006). These findings support the view of Witt et al. (1995) about the general nature of quadrupole systems and the inevitability of micro-lensing events in them. Further evidence of the continuous influence of micro-lensing is the time variability of the magnitude difference between the lensed components, which vary over a very large range.

As a recommendation, we think that the photometric adaptive PSF fitting method which has been developed by us is very promising, since it can be successfully applied to a very wide class of CCD frames. This applies to images and CCD frames with different kinds of distortion. Now we provided accurate values of the time delays in H1413 +117. On the other hand, due to the strong micro-lensing variability of the D component we should be more careful when deriving the time delay values between the pairs of the AD, BD, CD components. It would be very nice if these results are confirmed with independent observations.

A first paper dedicated to studies of gravitational lensing performed during my stay in Liège has just been published:
Koptelova E., Chen W.P., Chiueh T., Artamonov B.P., Oknyanskij V.L., Nuritdinov S.N., Burkhonov O., Akhunov T., et al. Time delay between images of the lensed quasar UM673 // Astronomy & Astrophysics, Volume 544, id.A51, 201

Another paper draft has been just prepared:
Akhunov T., Elyiv A., Artamonov B.P., Dudinov V.N., Nuritdinov S.N., Gaisin R., Delvaux C., Sergeyev A.V., Gusev A.S., Burkhonov O., Bruevich V.V., Zheleznyak A.P., Pelt J., Surdej J. Adaptive PSF fitting - a new photometric method and light curves of the GLS H1413+177 Clover Leaf: time delays and microlensing effects // MNRAS (draft)

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