

MIOSOTYS, a multi-object high-rate photometer designed for TNO serendipitous occultations

I-C. Shih^{*a,b}, Y. Boissel^a, H.-K. Chang^b, A. Doressoundiram^a, F. Roques^a, F. Dauny^a, P. Felenbok^a, A. Fernandez^a, J. Guerin^a, C.-Y. Liu^{a,b}

^aLESIA, Observatoire de Paris, Meudon, France

^bInstitute of Astronomy, National Tsing Hua University, Hsinchu, Taiwan

E-mail: stephen.shih@obspm.fr

MIOSOTYS (Multi-object Instrument for Occultation in the SOLar system and TransitorY Systems) is a multiple-object, high-speed photometer primarily designed for the observation of serendipitous stellar occultations by small (less than or of the order of 1 km at 40 AU) trans-neptunian objects as well as other high time resolution astronomical subjects. It is currently a visiting instrument to the 1.93m telescope at Observatoire de Haute-Provence (OHP), France. In this paper, we give a brief introduction to the TNO target select strategy and present the preliminary result of the first scientific observation in February 2010.

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*Speaker.

1. Instrument

MIOSOTYS is based on MEFOS (Meudon ESO Fibre Optical System) which is a multiple-fibre positioner first designed for multi-objects spectroscopy on the 3.6-m ESO telescope at La Silla, Chile in the 90s'. It remains in excellent shape and, recently, has been re-commissioned by LESIA, Paris Observatory to conduct high time resolution photometry. It has been implemented at the cassegrain focus of the 193 cm telescope at the Observatoire de Haute-Provence (OHP), France. The fibre positioner moves 29 arms to the targets within a field of view of 25 arc-minute. Each arm is equipped with an individual viewing system for accurate setting and carries one individual fibre that intercepts 12 arc-sec on the sky. Image of the 29 fibre bundle is projected onto a high speed EMCCD camera (see Figure 1).

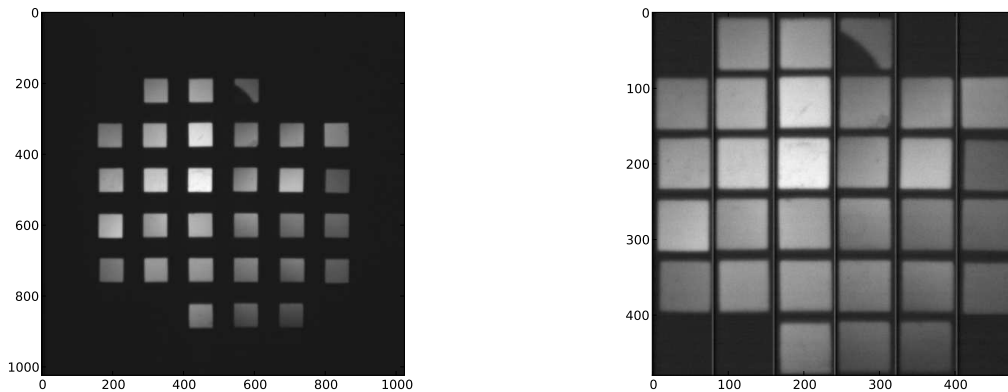


Figure 1: (Left) Full frame ($1,024 \times 1,024$ pixels) of the ProEM CCD camera with an image of the fibre bundle projected on. (Right) The individual fibre image block on the CCD frame can be selected and read out. This method reduces the image size to 480×480 pixels as well as decreases the readout time.

1.1 EMCCD Camera

We chose the ProEMTM camera manufactured by Princeton Instruments as the imaging sensor for the instrument. The e2v CCD201B is a back-illuminated, frame-transfer EMCCD with 1024×1024 image pixels (or active area 13.3×13.3 mm). The large image area can cover all of 29 fibre images. The peak Q.E. at 530 nm is 95%. The air cooling system maintains the operating temperature at -55°C and the typical dark current is ~ 0.008 electron/pixel/second. The readout noise then depends on the readout modes: low-noise (LN) and electron-multiplying (EM).

The EMCCD has dual readout amplifiers: LN is a conventional series register and EM is an extended multiplication register which provides 1 to 1000 times multiplication which can be controlled in linear, absolute steps. The dual ports design means that the camera can be optimized to perform different types of observations. For our primary scientific goal, we always operate under EM mode because of the fastest readout rate of 10 MHz. Although EM mode readout noise is significantly higher (50 electron rms at readout rate 10 MHz), it can be effectively reduced to $\lesssim 1$

electron rms when sufficient multiplication gain is applied. For more information about the camera characteristics and experiment configuration, one should refer to [1]

2. Trans-Neptunian Objects

Serendipitous stellar occultations by small Trans-Neptunian Objects (TNOs) requires right background stars to increase the probability of detection, namely stars on the ecliptic plane and located near the anti-solar direction. The star must have an apparent diameter, projected at the distance of the hypothetical TNO, smaller than the Fresnel scale F_s . In this case the event profile follows the Fresnel-Fraunhofer diffraction laws, and both distance and size of the responsible TNO can be retrieved with some analysis [2].

2.1 Target selection

The selection of stars is based on several factors: such as distance, temperature, spectral class, interstellar extinction as well as a model of the galaxy [3]. A combination of criteria on J , K and H_K (reduced proper motion in K band, introduced by Hertzsprung in 1919), defined with the model, allows to ensure the selected stars in the NOMAD catalog have a certain maximum apparent diameter.

2.1.1 Expression of the angular diameter of a star

A simple way to calculate a stellar angular diameter is to rely on perfect black bodies. Nevertheless, two problems arise when one tries to do this : Stars are not perfect black bodies, especially red dwarfs that have lots of heavy absorption bands in their spectra, and one has to deal with interstellar extinction. Then, the expression of the angular diameter α of a star is :

$$\alpha = \sqrt{\frac{L_{bol\odot}}{\pi\sigma}} \times \frac{1}{T^2\delta} \times 10^{-\frac{1}{5}(m_V - A_V + BC - M_{bol\odot})} \quad (2.1)$$

Where $L_{bol\odot}$ is the solar bolometric luminosity, σ is the Stéfan-Boltzmann constant, T is the star surface temperature, δ is 10 parsec expressed in meters, m_V is the star apparent magnitude, A_V is the interstellar extinction in V band, BC is the bolometric correction in V band, and $M_{bol\odot}$ is the solar absolute bolometric magnitude. Two other difficulties appear here :

- The equation depends on both physical and observational parameters, so we need a model to calculate the angular diameter. Then, we have to find an observational criteria that is common to stars with a small apparent diameter in the model, and apply it to a catalogue to select convenient stars for occultations by small TNOs.
- The bolometric correction both depends on spectral class and type. This means that for given T and A_V , a red dwarf and a red giant star will follow two different laws giving α in function of m_V .

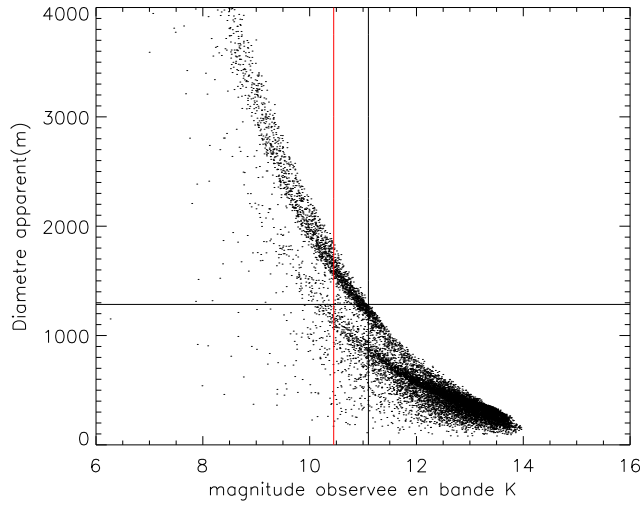


Figure 2: Evolution of projected apparent diameter at 40 $a.u$ with K -band apparent magnitude. Extinction has been estimated to 1.1 mag/kpc . The sky sample covers 5 squared degrees centered on position $RA = 86.405$, $DEC = 28.936$.

2.1.2 Evolution of angular diameter with the K -band magnitude

After estimation of the extinction on the sample of sky (5 squared degrees) both simulated by the model and downloaded from the catalogue, one can plot α in function of K band apparent magnitude (K band magnitudes are less sensitive to extinction), as it appears in the model data. The equation can also be written in K band, but to calculate α from K band magnitude, one needs BC in K band, which is hard to find in previous publications. From now on, we will speak about a projected apparent diameter at 40 $a.u$, mean distance of the classical Kuiper belt, instead of an angular diameter. Figure 2.1.2 shows what one gets. Note there are three laws appearing, pulled apart by the BC term in the equation. Then the upper curve is filled by red giant stars, the middle one by main sequence stars (including blue giants), and the bottom one by dwarf stars. Some stars are of course exceptions, but the huge amount of available stars up to V -band magnitude 16 allows to waste some of them.

On the figure are also shown two K -band magnitude limits, that ensure stars above to be smaller than F_5 at 40 $a.u$ and a wavelength of 550 nm . One is set in the situation where we take all populations from the sample, the other one in the situation where the red giant stars have been removed. One can note that we get brighter stars in the second case, but more stars in the first case. The best criteria would then be a combination of these two limits.

2.1.3 Reduced proper motion diagram (RPM) and estimation of interstellar extinction

To remove the red giant population, we use the reduced proper motions H_K of the stars in K band, and the $J - K$ **observed** color indices (apparent color indices + interstellar extinction). This leads to a reduced proper motion diagram (RPM), that is equivalent to a H-R diagram, with more

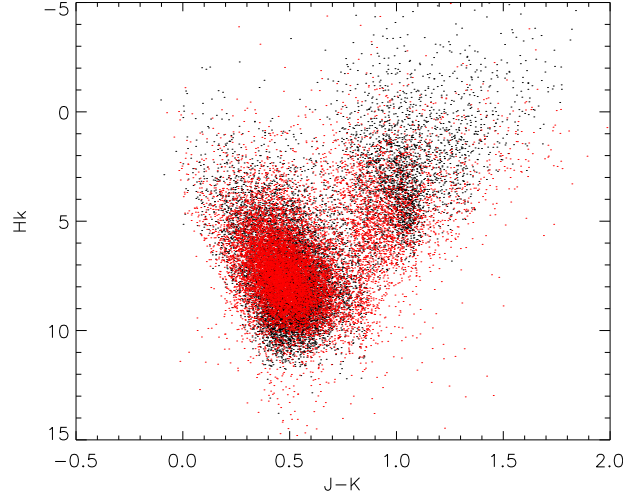


Figure 3: RPM diagram from model with estimated extinction in black, and superimposed, the RPM diagram derived from the measures in the NOMAD catalogue. Extinction has been estimated to 1.1 mag/kpc . The sky sample covers 5 squared degrees centered on position $RA = 86.405$, $DEC = 28.936$.

dispersion. The reduced proper motion is defined from the norm μ of a star proper motions in RA and DEC in a said X band as :

$$H_X = m_X + 5 \log \mu + 5 \quad (2.2)$$

To be compared to the absolute magnitude, used to build a H-R diagram, which is :

$$M_X = m_X - 5 \log D_{pc} + 5 \quad (2.3)$$

Where D_{pc} is the star distance in parsec, and m_X is the **observed** magnitude, i.e., apparent magnitude with interstellar extinction added. We make the assumption that all stars with V -band observed magnitude below 16 are in the neighborhood of the sun, thus have the same velocity around the Galaxy. Then μ is inverse proportional to distance and the two definition are equivalent. But there will be a higher dispersion in H_K than in M_K .

Both axes of such diagram depend on extinction, and a high extinction reduces the number of stars in the main sequence. Then, different diagrams, obtained from the model with different values of A_V will be shifted towards small H_K and big $J - K$. By comparison of the position of the median points of both diagrams from models and the catalogue, the extinction can be estimated. Figure 2.1.3 shows such diagram, with correct extinction, in black, with superimposed, the diagram from the catalogue, in red. The bottom left cloud is composed of main sequence and dwarf stars, the upper right cloud is composed of red giant stars.

2.1.4 Removal of red giants

We used a modified kingdom-means algorithm to find the best straight line that separates the two clouds. This line is then shifted to the barycenter of the clouds instead of the middle of the

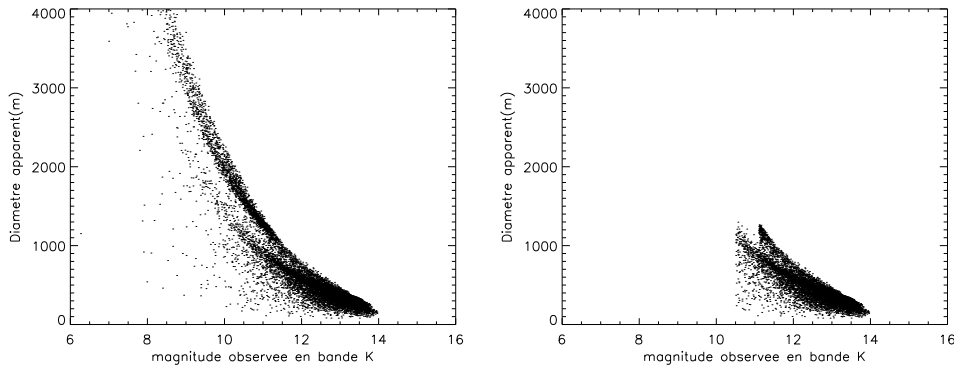


Figure 4: Left : Evolution of projected apparent diameter at 40 $a.u$ with K -band apparent magnitude. Right : Evolution of projected apparent diameter at 40 $a.u$ with K -band apparent magnitude of selected stars. Extinction has been estimated to 1.1 mag/kpc . The sky sample covers 5 squared degrees centered on position $RA = 86.405$, $DEC = 28.936$.

segment made by the two mean points, to ensure the removal of the maximum amount of red giants. With this, it is possible to set the criteria mentioned above. We get two ensembles of stars, selected with J and K magnitudes, and proper motions, that are observational parameters. The union of these two is the selected star population that have an apparent diameter smaller than the wished limit. Figure 2.1.4 shows the diagram of apparent diameter in function of K band apparent magnitude with only selected stars.

3. Preliminary result

MIOSOTYS has performed the first scientific observation in February 2010 at OHP. Currently we fix the experiment configuration (i.e. binning, exposure time, and EM gain) in order to simplify the onsite operating process, although we expect that these parameters will become adjustable in the future observations. Below we demonstrate early results such as the camera performance and the light curves of some targets.

CCD performance To detect occultations caused by small TNO objects requires typical time resolution of 0.1 sec or shorter, and signal-to-noise ratio of the target must be good enough to produce quality light curves. We compared a group of target stars for a range of magnitude 12 to 15 in V band against various experiment configurations. At this magnitude level, a hardware binning (2×2) and EM mode are always applied to enhance the signal. Figure 5 shows that, for most of the targets, intermediate EM gain level of ~ 400 and exposure time of ~ 0.05 sec is a reasonable experiment configuration for TNO observations. This parameter setup has been applied to recent observations.

Light curves Data are reduced and corrected with bias and flat field images respectively, the aperture photometry is then utilised to create the light curves (see [4] for detail data analysis pro-

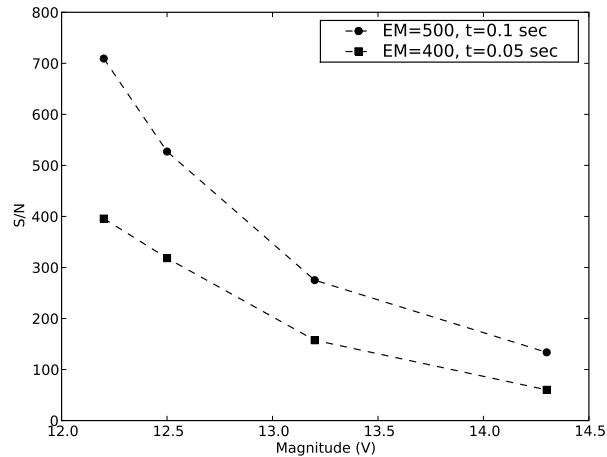


Figure 5: Comparison of S/N to different configurations of EM gain and exposure time. The results were derived from a group of stars observed in February 2010. The magnitudes are quoted from the NOMAD catalogue.

cesses). Figure 6 shows the light curves of several target stars for a range of magnitudes (notice: they are different targets from those in figure 5).

4. Summary

We present the early result of MIOSOTYS. Although the instrument is primarily designed for TNO serendipitous occultations, it is also suitable for other astronomical researches which require high time resolution ability, such as compact objects, flaring stars, binary stars, and etc..

Acknowledgments

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References

- [1] I-C. Shih, A. Doressoundiram, Y. Boissel, et al., *Introduction to MIOSOTYS: a multiple-object, high-speed photometer*, in proceedings of *SPIE 7735-149*, 2010
- [2] F. Roques, F., & M. Moncuquet, 2000, *A Detection Method for Small Kuiper Belt Objects: The Search for Stellar Occultations*, *Icarus*, 147, 530
- [3] A. C. Robin, C. Reylé, S. Derrière, & S. Picaud, 2003, *A synthetic view on structure and evolution of the Milky Way*, *A&A*, 409, 523
- [4] I-C. Shih, & Y. Boissel, *MIOSOTYS data reduction and analysis*, in preparation.

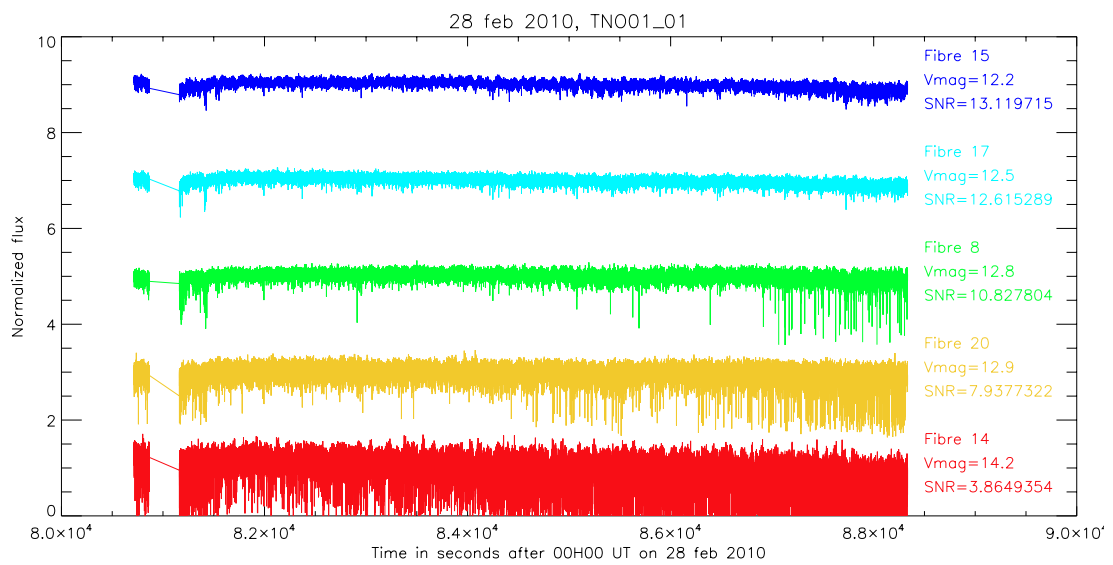


Figure 6: The light curves of target stars. The time resolution is 0.05 sec and EM gain stage is 400. SNR is the signal-to-noise ratio of the light curves.