Publ. Astron. Obs. Belgrade No. 92 (2013), 47 - 52 *Contributed paper*

FOLLOW-UP LUCKY IMAGING OBSERVATIONS OF *KEPLER* TARGETS

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Abstract. The image scale of *Kepler* space telescope is >4″/pixel, thus point sources are highly undersampled. Follow-ups with lucky imaging is therefore an essential observation for the proper interpretation of *Kepler* light curves, especially when there is a suspect for blending. Here I scketch how unobscured telescopes perform for this task.

1. INTRODUCTION

The concept of how lucky imaging can lead to photometry of objects that otherwise blend together. Using cameras with negligible read-out noise and applying exposure times of 1-15 msec, one will be able to identify the sky conditions when instantaneous Point Spread Function (PSF) is a singlet which is at most slightly blurred. This is usualy done with observing the Strehl-ratio in each individual images, and combining only the best few-percentile of all observations – when the atmosphere was locally very smooth with very little influence on imaging.

We succesfully tested an Andor IXon 888 EMCCD camera for this task (see e.g. Szabo et al. 2010), which is practically photon-limited fast imaging system, able to run in photon counting mode. This is thank to the EM-pre-amplification before read-out, thus setting very high pre-amplification gains (in the order of 100 to even 1000), the read-out noise is highly outscored by photon noise, thus the system will be practically free from read-out noise.

Attached to the 1-meter RCC telescope of Konkoly Observatory, this camera is able to go to as faint as 10 magnitude limit with exposure times of 1–15 msec. Involving only the best 1-2% of all images in synthesis, we can get close to the quality of the image with the given instrument, but lacking speckle patterns and blurring of the atmosphere.

2. THE PROBLEM OF UNDERSAMPLING

There are 42 CCDs of 2200×1024 pixels size in *Kepler* camera head, leading to $M \approx 9.4 \times 10^7$ pixels. Following to the well-known "birthday paradox" of statistics, one can estimate the probability of having at least one blend if N stars are imaged, in linear approximation we have[1]

$$P(blend \mid M, N) \approx 1 - e^{\frac{-M^2}{2N}}. \tag{1}$$

The surprising result is that if there were (only) 12,950 stars in the 94 Mpixel *Kepler* field, there would be 50% probability to have two stars blending in the same pixel. But instead of 12,950 stars, there are three orders of magnitude more, ≈13 million objects in the Kepler Input Catalog (KIC), leading to the conclusion that practically all stars in the *Kepler* field are blended.

This blending can be partially resolved relatively easily, because the pixel size of *Kepler* images, $> 4''$, is well above the resolution power of Earth-based instruments. Thus the strategy is to get as good resolution as possible and map at least the "microfield" around the most interesting KIC-objects. With this tool, one will be able to decide on

- The source of the interesting light variation;
- The light contamination from "not interesting" stars;
- The correction to this light contamination;
- And on the unbiased color indices of the surveyed object.

3. INSTRUMENTATION

Currently we could test the technique on telescopes designed for long exposures. Because seeing is very rarely below $1''$ from any site in Hungary, and these telescopes were designed for seeing-limited observations, these instruments have nonradial PSF distortions in the order of 0.6–$0.8''$.[2] Therefore, there are two ways for lucky imaging:

- image synthesys (or image reconstruction – "deconvolution" for extended objects), when the observed image is reconstructed as a set of point sources convolved with the known PSF, the unknowns are usually the astrometry and photometry; or
- constructing diffraction-limited optics with large Strehl ratio.

For the first possibility we performed detailed analyses in the case of the hierarchical triplet HD 181068 (i.e. Trinity; Derekas et al. 2011), and KOI-13, to identify securely the planet host in an Aitken's double star Szabó et al. 2011). We also give an imagery in Fig. 1 of present paper.

[1] see `http://mathworld.wolfram.com/BirthdayProblem.html` for detailed derivation. Also here you can find a formula to estimate the probability function of having k-fold blends if you have N stars in M pixels.

[2] Which is natural. Building a telescope optics for seeing limited observations with much better PSF than your best seeing would evidently be a waste of money.

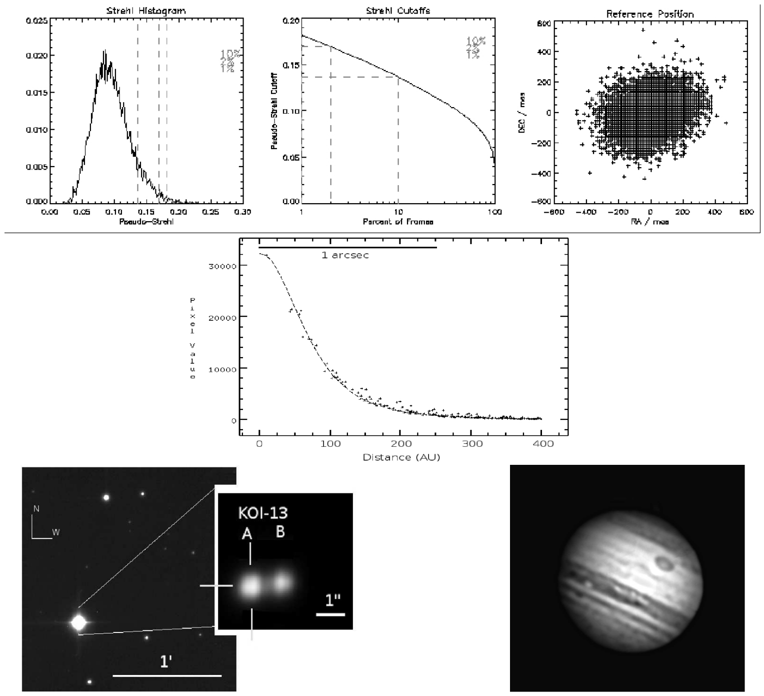

Figure 1: Upper panels: Density (left) and cumulative (middel) distribution of Strehl ratio in case of HD 181068. Top right: the standard deviation of astrometry is ≈100 mas in both coordinates for each individual images with large Strehl ratio. Middle: The environment of HD 181068 with lucky imaging shows no additional companions (Derekas et al. 2011). Bottom left: Wide-field and lucky image of the field with KOI-13. The size of the inset is exactly 1 *Kepler*-pixel. Bottom right: Jupiter with lucky imaging with the 1-meter RCC telescope (no additional image reconstruction has been applied).

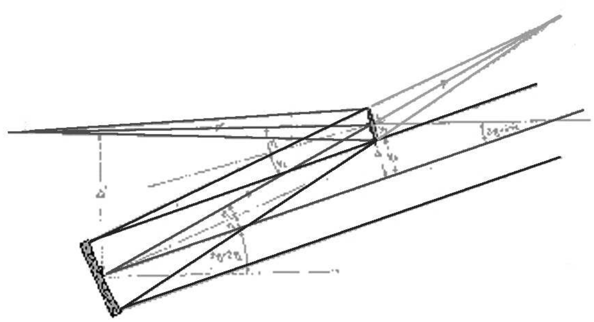

Figure 2: The scetch of the prototype Kutter telescope after Kutter's original book (1953). The primary mirror was an f/14.7 concave sphere with 110 mm diameter, the secondary was a convex sphere at 965 mm distance. The coma astigmatism was 2μm without an additional coma corrector.

Here I rather wish to concentrate on a possible new instrument designed for diffraction limited lucky imaging. Beside the accuracy of optical elements, the optical configuration is also extremely important. RCC or Cassegrain telescopes are quite suboptimal due to the large central obscuring by the secondary mirror. This results in a considerable light loss, and more importantly, dramatical decrease of the Strehl ratio. Centrally covered optics, id est, have slightly narrower disk but also highly amplified diffraction rings, and the contrast of this optical system is rather low. This results in much noise in image reconstruction steps. E.g. Gemini telescopes have a Strehl ratio of 30–55% in K-band even with active optics.[3] The RCC telescope at the Piszkéstető station of Konkoly observatory has a Strehl ratio around 25% at tranquil seeing conditions (Fig. 1).

Unobscured optics offer highly larger Strehl-ratio, because the central part of the aperture – which is the most important part to get contrast – can also collect light with full capacity. Tilted mirror telescopes such as Kutter and Yolo systems, can perform a Strehl ratio above 90% if the mirrors have accurate surface and positioning. This is close to the Strehl-performance of lens telescopes at ≈ 94–96%. The central peak provided by an obscured telescope contains as many photons if it has 1.7–2 times the diameter than a reference unobscured telescope. In other words, *if your telescope in unobscured, you can double the diameter in mind for lucky imaging performance.*

4. CONCLUSION

My suggestion is therefore designing and building a 0.6–0.8 meter unobscured telescope with very slightly oversampled imaging (e.g. diffraction limited FWHM≈3 pixels), dedicated for lucky imaging and fast photometry on the lucky basis. This instrument will be as fast as a ≈1.2-meter obscured telescope in lucky imaging performance, will provide a diffraction-limited resolution of 0.2″, and under favourable seeing conditions, the diffraction limited resolution can be approximated in practice, too. This telescope will be, on the other hand, lightweight and small enough for a relatively easy installation, and remote controll will be possible with simple technical support.

Turning to the *Kepler* field, the performance of this instrument will be similar to what a 30 Gpixel kamera head would provide in *Kepler* space telescope. This telescope will even not completely solve the blending problem in the *Kepler* field, but for one single blend with 50% probability there will be a need for 200,000 stars (15 times more than for *Kepler* space telescope), deepening the limit of unblended stars by 2 magnitudes; and offering a secure resolution in >99% of *Kepler* bands.

ACKNOWLEDGEMENTS. This project has been supported by by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the Hungarian OTKA Grants K76816, K83790, K104607, MB08C 81013, a “Lendület-2009 Young Researchers” Program of the Hungarian Academy of Sciences. dI am grateful to the LOC, SOC and all contributors to the memorable BELISSIMA Conference in Beograd.

[3] http://www.noao.edu/meetings/ao-aas/talks/Christou_Gemini_AO_AAS.pdf

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