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Characterizing the KL4040 sCMOS camera for use at the Boyden observatory

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Recently the marked improvement and availability of scientific CMOS (sCMOS) cameras has provided an alternative to more expensive CCD based cameras. A Kepler KL4040 sCMOS has been acquired from Finger Lakes Instrumentation to replace the current CCD camera used on the UFS Boyden 1.5 m telescope. Because of the differences between CCDs and sCMOS sensors, the sCMOS camera is currently being characterized and tested. The camera was first mounted to a 14" Celestron CGE 1400 system with an Apogee FW50-7S filter wheel with Johnson-Cousins $UBVR_CI_C$ filters for the first on-sky and star-light tests. These included absolute photometry of the standard field SA107 in the BVR_CI_C filters using differential photometry and using the determined colour coefficients. Thereafter the camera was moved to the Boyden 1.5 m telescope and mounted on the Photometer Instrument-pack with a Johnson-Cousins $UBVR_CI_C$ filter system. After integration into the Boyden 1.5 m telescope systems, additional on-sky tests were performed, including fast photometry of one full orbital period of 3.56 h of the cataclysmic system AR Scorpii at ≈ 6-7 s cadence. All of the results were processed using a custom python pipeline created using libraries including **astropy, numpy** and **ccdproc**.

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1. Introduction

A Finger Lakes Instrumentation (FLI) Kepler KL4040 scientific Complimentary Metal-Oxide Semiconductor (sCMOS) camera was acquired for Boyden observatory. Because of the difference in how a sCMOS operates as opposed to a CCD, the camera had to be thoroughly tested and characterised to determine how it will respond when used on a telescope system. Initial tests were undertaken in a laboratory setting to determine the detector's thermal stability, noise patterns in the images, and the photo-response, as well as the software interface for operating the instrument (see [1]). The results showed that, as expected, the sCMOS camera has a higher dark current and is more sensitive to thermal changes than the current CCD detector, which must be carefully considered during operation, but which can be mitigated. The detector's photo response was very linear (R=0.999) over the full 16-bit range (combined from two 12-bit readouts), up to the non-linear limit at about 98% of the full well. It was also found that the fixed pattern noise, inherent to the sCMOS detector, was satisfactorily removed during standard image reduction processes. In this proceedings we report on the initial on-sky testing that were performed.

2. On-sky Testing

2.1 Standard Star Fields

On-sky testing consisted of observing Landolt Equatorial Standard stars, recorded in the SA107 AAVSO database (see the AAVSO database [2]), with the sCMOS mounted to a Celestron CGE1400 telescope system. The KL4040 was cooled down -15°C for this test. The magnitudes of the standard stars were measured in the BVR$_C$I$_C$ filters. To transform the instrumental magnitudes to apparent magnitudes, the processes and equations outlined in the paper by Benson, P.J. [3] and AAVSO note by Sarty, G. E. [4] were used. The process describes how to find transformation coefficients for each filter used. The measured data was used to plot the graphs $B-V$ vs $b-v$, $V-R$ vs $v-r$, $V-I$ vs $v-i$ and $R-I$ vs $r-i$ and the inverse slopes of the best fit lines were used to find the respective colour transformation coefficients T_{bv}, T_{vr}, T_{vi}, T_{ri}. Similarly the graphs for $B-b$ vs $B-V$, $V-v$ vs $V-R$, $R-r$ vs $R-I$, $I-i$ vs $R-I$ were plotted and the slopes of the best fit lines were calculated to find the transformation coefficients T_b, T_v, T_r, T_i. Note that the capital filter colours denotes the known magnitude values as listed in the AAVSO database and the lower-case letters denotes the measured magnitude values. The transformation coefficients were then used to transform the measured magnitudes to apparent magnitude using differential photometry and equations 1 to 5. Using this method the observer does not need to account for the airmass or extinction. The results were compared to the known results to see how accurate the transformed values were. The signal to noise ratios (SNRs) were also determined to compare the brightness and the achieved SNRs of the stars to one another.

$$(R_t - I_t) = (R_c - I_c) + T_{ri}((r_t - i_t) - (r_c - i_c)) \tag{1}$$

$$R_t = r_t + (R_c - I_c) + T_r((R_t - I_t) - (R_c - I_c)) \tag{2}$$

$$I_t = R_t - (R_t - I_t) \tag{3}$$

$$V_t = v_t + (V_c - v_c) + T_v T_{vr}((v_t - r_t) - (v_c - r_c)) \tag{4}$$

$$B_t = V_t + (B_c - V_c) + T_{bv}((b_t - v_t) - (b_c - v_c)) \tag{5}$$

2.2 Fast Photometry on AR Scorpii

The camera was mounted on the Boyden 1.5 m telescope for doing fast photometry on AR Scorpii on the night of 12 July 2023. AR Scorpii is a binary system consisting of a secondary red dwarf star and a primary white dwarf (WD) star with a system orbital period of 3.56 h. The system also exhibits pulses in brightness over 118.2 s, originating from synchrotron radiation from the pole caps of the WD. The camera was used to complete short 5 s exposures over a period of 3.8 h to cover the full 3.56 h orbital period as reported by Marsh et al [5]. This cataclysmic variable (CV) system shows strong variability of up to 2 mag, perfect to test the throughput of the sCMOS on rapid exposures conducted for several hours. The exposures were done in a clear filter and a binning of 2x2 was used to collect as much light as possible for this test. The camera was cooled down to -20°C for this test.

3. Results & Discussion

3.1 Standard Field

For the standard field tests, using BVR_CI_C filters, 8 consecutive observations for each filter, with 8 s exposures per filter were made. Longer exposure times on the Celestron CGE1400 telescope proved to be problematic, as the tracking was not satisfactory. The averages of the eight observations, for each star, were then used to calculate the transformation coefficients namely, T_{bv}, T_{vr}, T_{vi}, T_{ri} and T_b, T_v, T_r, T_i. These values were then used to calculate the transformed apparent magnitudes for the BVR_CI_C filters. Table 1 shows the known apparent V magnitude and the calculated apparent V magnitude using the colour transformation coefficients calculated from the observations. Refer to Fig. 1 for a sample image of part of the SA107 field with stars marked per ID as referenced in Table 1.

ID	AUID (AAVSO)	V Mag (Catalogue)	V Mag (transformed)	SNR (Obs)
b0	000-BJZ-200	13.054 (0.002)	13.129	41.227
b1	000-BJZ-203	13.121 (0.006)	13.161	38.929
b2	000-BJZ-204	12.919 (0.002)	13.027	44.245
b3	000-BJZ-208	11.847 (0.003)	11.944	113.550
b4	000-BJZ-207	11.676 (0.004)	11.745	132.024
b5	000-BJZ-209	12.284 (0.001)	12.343	80.560
b6	000-BJZ-216	12.116 (0.003)	12.188	91.739
b7	000-BJZ-218	14.256 (0.006)	14.299	13.504
b8	000-BJZ-217	14.329 (0.006)	14.186	14.913
b9	000-BJZ-219	13.926 (0.006)	14.023	17.313

Table 1: List of SA107 field stars in the V-band. The ID corresponds to the number on Fig 1

With an exposure time of only 8 s the SNRs of all the stars were between 13 and 132 for the V filter. Considering this the transformed values still correspond well to the known values, as all the transformed values are within 2% of the catalogue magnitude values.

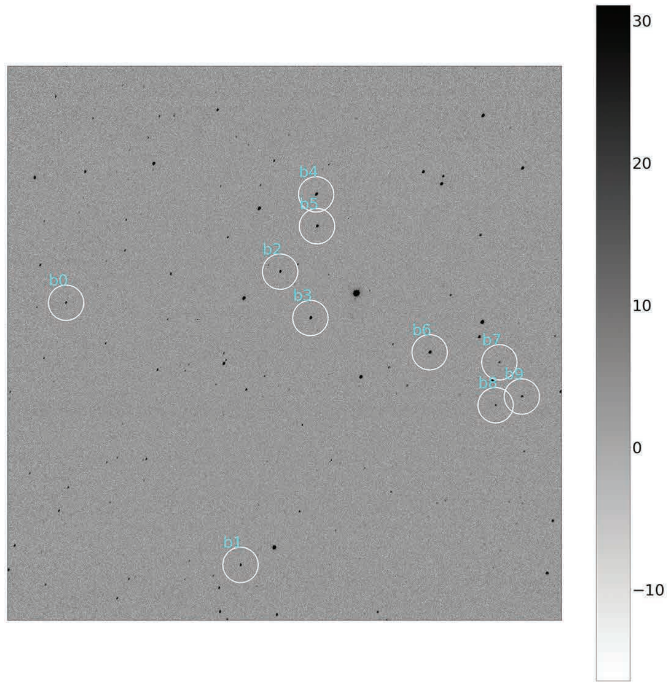

Figure 1: Part of the SA107 field showing some of the stars used for the standard field photometry in the V band taken with the KL4040. Scaling is in relative counts.

3.2 Fast Photometry

The observations of AR Scorpii covered 1.07 orbital periods. The variations in the light curve comes from the 118.2 s beat period of the CV system and this was verified by running Lomb-Scargle (Fig. 3) on the light curve (Fig. 2) and folding the data on the peak period identified as 118.2s (Fig. 4). The two peaks in Fig. 3 shows the frequency of the beat period at 0.0084 Hz and the harmonic at 0.0169 Hz. Fig. 2 shows the observed differential photometry light curve of AR Scorpii. The light curve shows the most variation at about 2300 s and 10000 s with a comparable pattern seen in [6]. The variability in the light curve are accordingly explained as the superposition between the spin and beat pulses, around the slower modulation of the orbital motion.

This result shows that the KL4040 camera is capable of doing fast photometry as it could produce a light curve of AR Scorpii that clearly shows the sinusoidal variation in magnitude as the two stars orbit one another, as well as the 118.2 s beat period of the spinning WD contained in the observed pulsations. This spinning of the WD is revealed by the double peak phase folded light curve (Fig. 4), which is due to the observed bright polar regions, one at each peak.

4. Conclusion

The KL4040 operated well during the standard field tests, as the colour transformation coefficients that were determined for the setup on the Celestron telescope and the instrumental magnitudes for the standard stars were transformed to apparent magnitudes with an accuracy within 2% for all observed stars. Similar results should be possible on other telescope setups after going through the same process.

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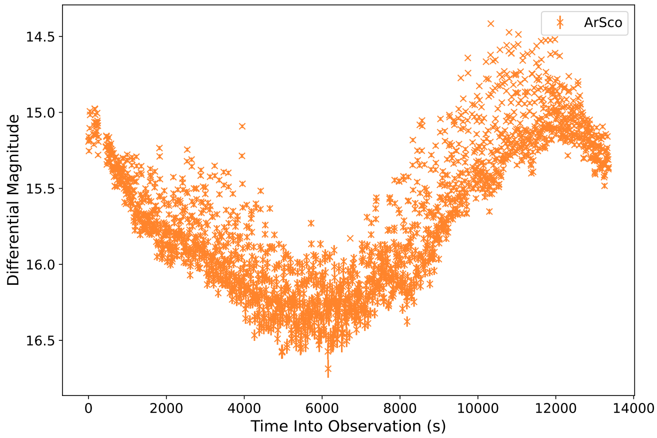

Figure 2: Light curve of one complete orbital period of AR Scorpii.

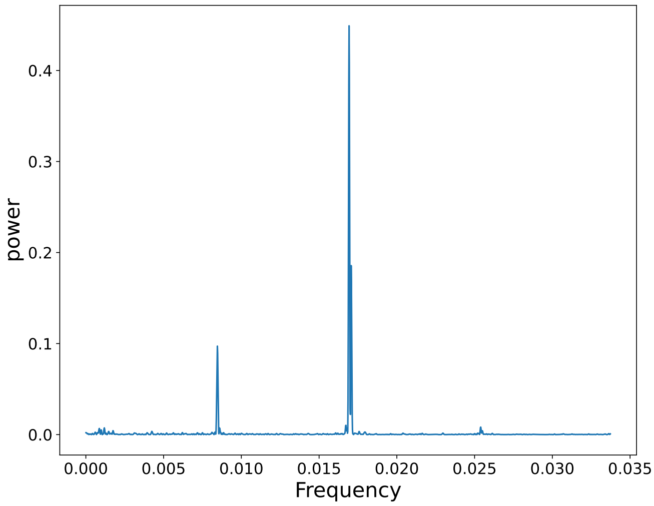

Figure 3: Power vs Frequency graph that shows the peak frequencies of the light curve of AR Scorpii detected by Lomb-Scargle.

The fast photometry data was able to observe the light curve of one full orbital period of AR Scorpii. The beat period of 118.2 s, reported in [5], was found using Lomb-Scargle, with the measured beat period phase folded data clearly showing two peaks. The KL4040 achieved a cadence of 5 - 7 s with 5 s exposures and 1 - 2 s of overhead between images using an USB 3.0 connection. The manufacturer also reported up to 20 frames per second readout when using a QSFP-2 connection and although untested, it might mean that the KL4040 could be a cost effective way of achieving sub-second readout rates for doing fast photometry on selected sources.

Taking all of the above tests into consideration the KL4040 sCMOS is capable of competing with CCDs in its price class, but it will still depend on the observational plans and projects of the observatory. The performance of the KL4040 on extremely faint objects that has to be observed in different colour filters for short amounts of time is not yet on par with CCDs.

Future plans will focus on testing the KL4040 at the Boyden Observatory to find the limitations

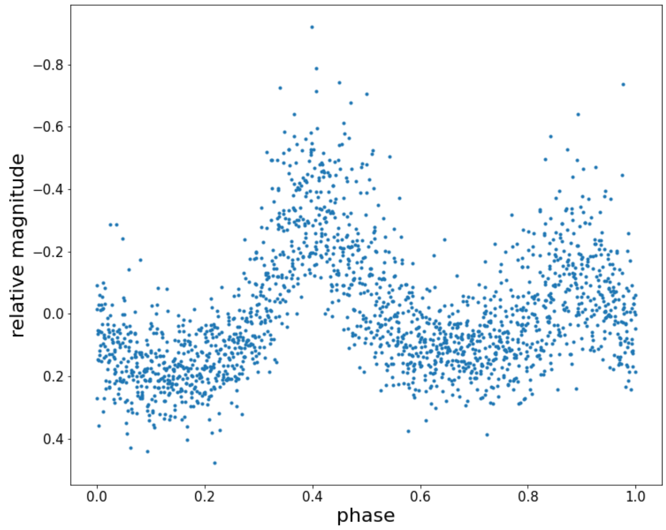

Figure 4: Folded light curve on the beat period of AR Scorpii.

of the sensor like the faintest detectable sources. The noise and image structure characteristics will also be analysed to see if any odd noise is present on the KL4040 sensor. The analyses will then be used to compare the KL4040 to other sensors.

References

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[2] AAVSO, *SA107 Standard Field*, https://app.aavso.org/vsd/stdfields.

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