Astro Skipper-CCD Characterization for Cosmological Applications

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INTRODUCTION

Cosmology is the study of the universe, regarded as a whole. The universe is richly textured, with structures on a vast range of scales. Determining the matter-energy density of the universe is a core measurement in cosmology. Over the years, cosmologists have dedicated time and effort to determine this distribution. This effort has uncovered that the majority of the universe is composed of dark energy and nonbaryonic dark matter.

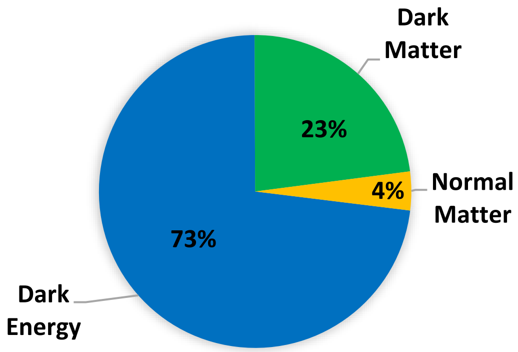

Figure 1: Matter-Energy density of the known universe [1]

Dark energy is an unknown form of energy, which is defined to be the cause of the accelerating expansion of the universe. This mysterious energy has been measured to account for more than 70% of the known universe [1]. In 1929, Edwin Hubble discovered how the wavelength of light emitted from distant galaxies is shifted towards the red end of the electromagnetic spectrum [2]. He found that more distant galaxies showed a large degree of redshift while closer galaxies showed less. Cosmologists later determined that this occurs because the universe itself is expanding, thus stretching the light over time and space. More recent discoveries show that the expansion of the universe is accelerating [1]. However, little is actually known about the fundamental nature of dark energy.

Dark matter is a form of matter that cannot be detected electromagnetically. However, cosmologists are confident it exists because of its gravitational effect on galaxies. When examining the overall structure of the universe, there is simply not enough visible matter to account for the formation and clustering of galaxies. Furthermore, in spiral galaxies, we observe stars that orbit at speeds that cannot be accounted for by the gravitational force of visible matter. These are only two examples of observational indications that there is "something" in and around these structures that interacts gravitationally.

In the effort to further understand these phenomena, cosmologists are limited to indirect detection methods. Such methods include, but are not limited to, observing the orbital speeds of stars in spiral galaxies, the radial velocity of galaxies within large clusters, and the effect of gravitational lensing by dark matter. Such methods require powerful telescopes and imaging tools that provide accurate image information to interpret.

Today, the Dark Energy Survey takes on the task of observing hundreds of millions of galaxies with the help of one of the strongest CCD cameras currently in use in astronomy, the Dark Energy Camera (DECam). DECam records images using filters which span from 400 to 1080 nm. These images are taken on a focal plane that contains 62 specially designed, state of the art CCDs [3]. CCDs, or charge-coupled devices, are similar to the devices inside of most digital cameras one would use today. However, unlike average cameras, which are used to record images that are very bright, astronomical CCDs are designed to detect very small amounts of light coming from very faint objects.

SCIENTIFIC CCDs

History & Operation

A charge-coupled device (CCD) is an electronic light sensor used in various devices and scientific applications. It was invented in October 1969 by Willard S. Boyle and George E. Smith at Bell Telephone Laboratories [4]. While originally conceived as a memory device, it became clear that the CCD possessed a wide range of applications. One of the primary beneficiaries of CCD technology was astronomers, who were interested in the detection of photons from great distances would benefit from a scientific CCD.

The CCD is segmented into a large array of light-sensitive areas called pixels. When a photon falls within the area defined by one of the pixels, it is converted into one (or more) electrons by a process known as the photoelectric effect. The number of electrons collected is directly proportional to the intensity of the light falling upon a pixel. Each pixel consists of a metal-oxide-semiconductor (MOS) capacitor (Figure 2), which allows for the transfer of charges across the device. By manipulating the voltages on the gates of the capacitors, the charges are allowed to spill from one capacitor to the next [4].

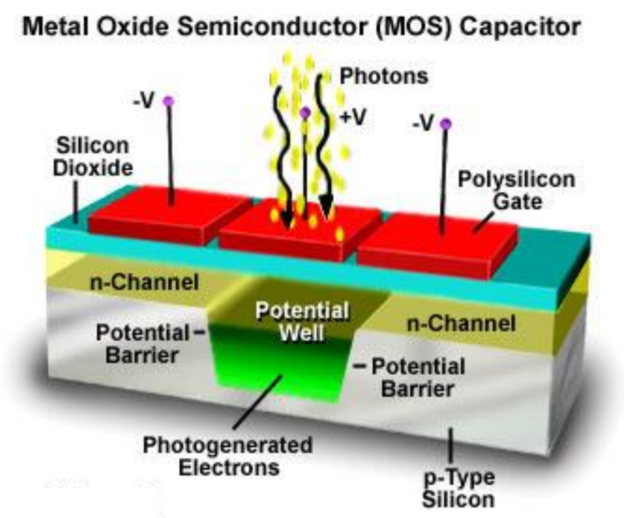

Figure 2: Metal Oxide Semiconductor (MOS) Capacitor architecture[2]

There are many ways to arrange MOS capacitors to form a CCD imager array. Typically, the simplest CCD is a three-phase device. In this arrangement, the gates are arranged vertically in parallel with every third gate connected to the same clock driver, as seen in Fig. 3. The CCD image is read out by a succession of vertical shifts through the vertical registers. For each vertical shift a line of pixels is transferred into a horizontal register which is oriented at right angles to the vertical registers. Before the next line is shifted, the charge in the horizontal register is transferred to the output amplifier. The amplifier converts the charge contained in each pixel to a voltage, and the device is serially read out line-by-line, pixel-by-pixel, representing the scene of photons incident on the imager array.

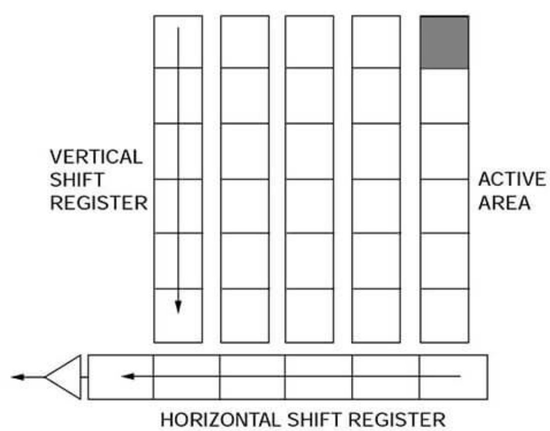

Figure 3: Structure of vertical and horizontal shift registers in CCD pixel frame[3]

Skipper CCDs

In all CCDs, precision measurements are limited by many factors, one of which is the readout noise of the CCD electronics. Electronic readout noise is added to the image signal by the output amplifier and results in variations in the voltage measured on each pixel. A new CCD

[2]https://www.olympuslifescience.com/en/microscoperesource/primer/digitalimaging/concepts/moscapacitor/

[3]https://www.hakuto.com.tw/tw/products_d.php?p=196

design, with the purpose of reducing low-frequency readout noise, utilizes a floating gate output stage [4] to perform repeated measurements of the charge in each pixel. This readout technique has been implemented in the form of a “Skipper” CCD. The low readout noise achieved by Skipper CCDs allows charge measurement at the accuracy of individual electrons simultaneously in pixels with single electrons and thousands of electrons.

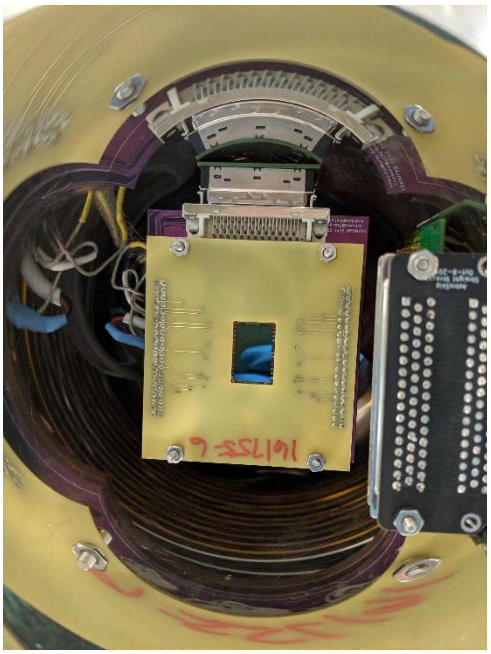

Figure 4: Backside-illuminated CCD package mounted inside the Astro dewar

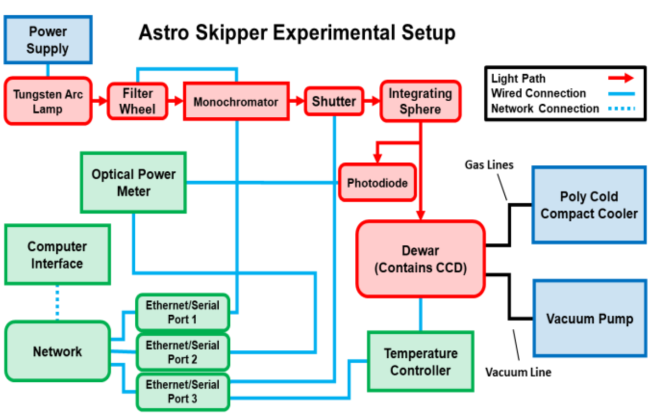

Figure 5: Diagram of components that comprise the Astro Skipper testing station.

An additional feature of the Skipper CCD is its ability to perform “Smart Skipper” (targeted) readout. This feature enables the user to select a specific region of the CCD array to perform multiple samples. This grants the flexibility to readout a subset of pixels with low noise, while reading the rest of the pixels quickly.

One great advantage of CCDs when compared with other detectors is their linear response to incident light. Linearity means that there is a simple linear relation between the input value (charge collected from incident photons), and the output value. In addition, the sensitivity for the optical spectral range makes CCDs the natural choice for astronomical applications. In our case, the Skipper CCD is the ideal detector for cosmological research.

PROJECT FOCUS

The overall focus of my summer project was to characterize the response of a Skipper CCD with respect to optical light, and with the intention of using this detector in cosmological applications. It is important for us to properly characterize the CCD in order to have a good physical understanding of the properties and function of the detector. With this focus in mind, the work I did was divided between two areas: hardware and analysis.

On the hardware side of my project, I was responsible for assembling and calibrating, when necessary, each component of a new optical testing system. On the analysis side, I was responsible for developing the Python scripts that carry out the characterization tests for the detector. This involved using single-sample and multi-sample image data to develop repeatable tasks that can be used to characterize any Skipper CCD.

EXPERIMENTAL SETUP

This section describes the components and assembly of the Astro Skipper testing station. The testing station is composed of a standard set of optical equipment that allows for illumination of the CCD surface in the desired wavelength. The CCD is mounted in a thermally controlled vacuum dewar that is cooled to an operating temperature of ~140K and pumped down to ~1×10^{-5} torr. The Infrared Laboratories vacuum dewar used in this testing station is designed specifically to be mounted on a telescope, making it an integral component of our testing station.

Various components, such as the shutter, monochromator, optical power meter, and temperature controller are controlled via ethernet-to-serial ports. These gateways translate commands written in Python scripts to the corresponding serial device. The commands serve two purposes: either to inquire the current measurement or to adjust the current device settings.

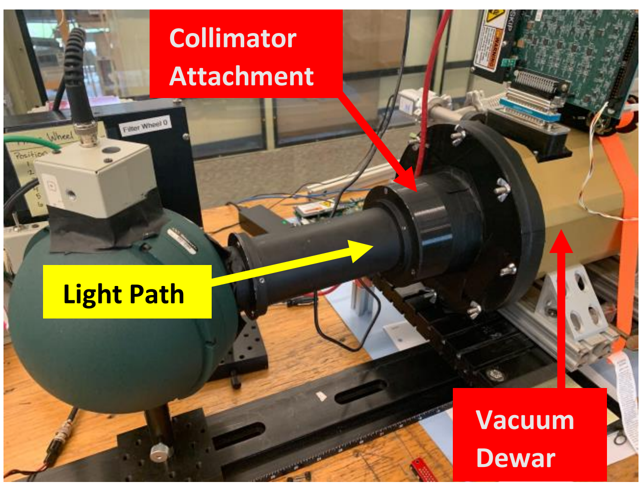

Figure 6: 3-D printed collimator attachment shown attached to the standard optical collimator and Astro vacuum dewar.

In order to connect the light path from the source lamp to the window of the vacuum dewar, I needed to design a special attachment that was compatible with both the vacuum dewar and the standard optical equipment. To accomplish this, I utilized Autodesk Fusion 360 to create a 3-D model of the attachment. Once the model was completed, the component was 3-D printed in-house at the Si-Det facility (Figure 6). To minimize the amount of ambient light entering the vacuum dewar, we utilized Black PETG polymer as the printing material. PETG is a thermoplastic polymer that provides significant chemical resistance, durability, and excellent formability for manufacturing, making it a suitable choice for our needs.

Once printing was completed, I added three threaded heat-set inserts that would allow us connect the printed component to the standard optical equipment on hand. With this component printed and the threaded inserts in place, the light path to the vacuum dewar was completed.

Ambient light leaking into the vacuum dewar proved to be a consistent point of concern, and thus further methods were implemented to reduce possible leaks. First, an additional light blocking cloth was put in place to cover all areas prone to light leakage. In addition, we constructed a black box that covers the entire vacuum dewar, shielding it from ambient light in the room. With these coverings in place we saw a significant reduction in ambient light entering the vacuum dewar.

Figure 7: Ambient light blocking cloth and black box covering the Astro Skipper testing station.

DATA ANALYSIS

With the Astro Skipper testing station completed, we began performing tests to characterize the Skipper CCD. In general, each CCD is characterized by its linearity, quantum efficiency (sensibility), gain and readout noise. Using the Python programming language, I assisted in developing scripts that perform a few of these tests. This section will describe the results of such tests for a backside-illuminated Skipper CCD.

Photon Transfer Curve

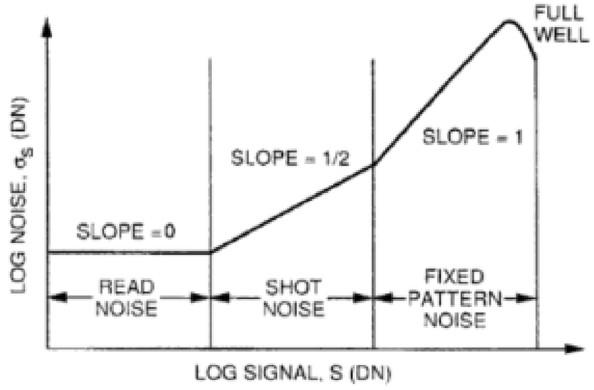

Figure 8: Photon Transfer Curve diagram illustration three noise regimes over the dynamic range of the CCD

The photon transfer curve illustrated in Fig. 9 is a response from the Skipper CCD that was uniformly illuminated at different levels of light with 200 samples taken in each image. We plot the noise or standard deviation as function of average signal, for a group of pixels contained on the CCD array. The data is plotted on a log-log scale in order to cover the large dynamic range of the CCD.CCDs can be thought of as having three noise regimes: read noise, shot noise, and fixed pattern noise.

Read noise sets a noise floor for the device. This noise is ultimately limited by on-chip amplifier noise, but can represent any other noise sources that are independent of the signal level.

As the illumination of the CCD is increased, the noise becomes dominated by the shot noise of the signal. Shot noise is associated with the random arrival of photons on the CCD as governed by Poisson statistics. Some pixels intercept more photons that others, which accounts for the variance seen in pixel values. Since the plot is on a log scale, the shot noise is characterized by a line of slope ½. This slope arises because the uncertainty in the quantity of charge collected in any given pixel is proportional to the square root of the number of incident photons [4].

Finally, for large signal values, the noise is associated with fixed-pattern or pixel nonuniformity that results from sensitivity differences among pixels. Pixel nonuniformity is a result of processing variation when the CCD is fabricated. This problem generates pixels with different responsivities or effective sizes.

The onset of full well (saturation) is observed at some illumination level within the fixed-pattern noise regime. At this point the charge spreads between pixels, smoothing and lowering the noise component as seen in Fig. 8.

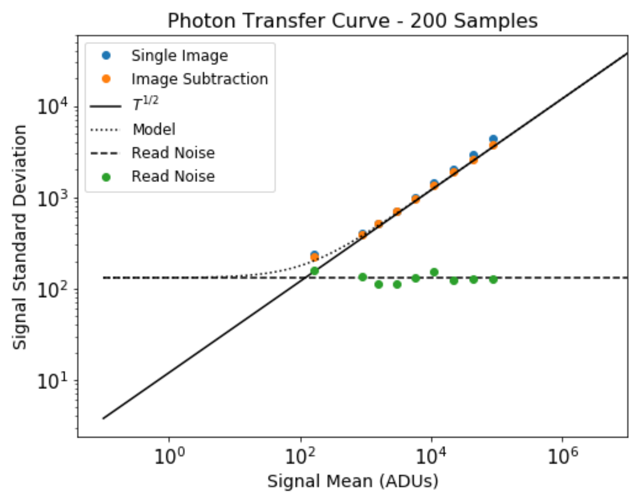

Figure 9: Response from Skipper CCD uniformly illuminated at different levels of light w/ 200 samples

Examining the plot in Fig. 9 we see the noise floor is relatively stable at a standard deviation of approximately ~$1x10^2$ ADU. In the shot noise regime, we expect the uncertainty in charge collect by any given pixel to follow a slope of ½ (as governed by Poisson statistics). Not illustrated on this plot is the onset of full well or saturation. This feature is not present due to the low illumination of the CCD. If exposed to light for longer time periods, this CCD would eventually reach that point of saturation.

Single Electron Resolution

The low readout noise achieved by Skipper CCDs, coupled with a stable linear gain, allows charge measurement at the accuracy of individual electrons simultaneously in pixels with single electrons and thousands of electrons [5].

The "gain" of a CCD camera is the multiplicative conversion between number of electrons (e-) captured by the detector and the number of analog-to-digital units (ADU) contained in the CCD image. Gain is given in electrons per ADU (e-/ADU). While there are different methods of measuring gain, we implemented a fairly simple method utilizing Poisson statistics.

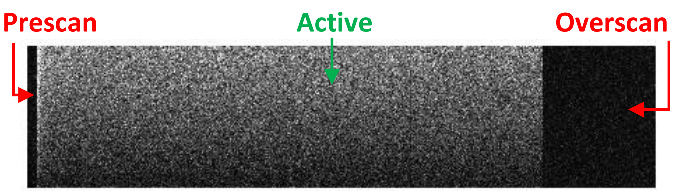

Figure 10: Skipper CCD image (100 rows x 450 columns, 200 samples) displaying active, ovsercan and prescan areas.

By measuring the mean and variance of the active and overscan areas, the gain can be calculated as the ratio of differences of the mean and variance in each region (equation shown below).

$$Gain = \frac{Mean(active) - Mean(overscan)}{Var(active) - Var(overscan)}$$

From this equation we calculated a gain of 0.005 e-/ADU for this detector. With a known gain, the pixel values can now be interpreted in units of electrons. By only taking 200 samples per pixel, we were successful in reaching single-electron resolution (Figure 11). The peak at 0 e^- has rms noise of $0.24e^-$ rms/pix while the Gaussian fits show an average rms noise of $0.24e^-$ rms/pix. This measurement demonstrates the single-electron sensitivity afforded by the low readout noise achieved by Skipper CCDs.

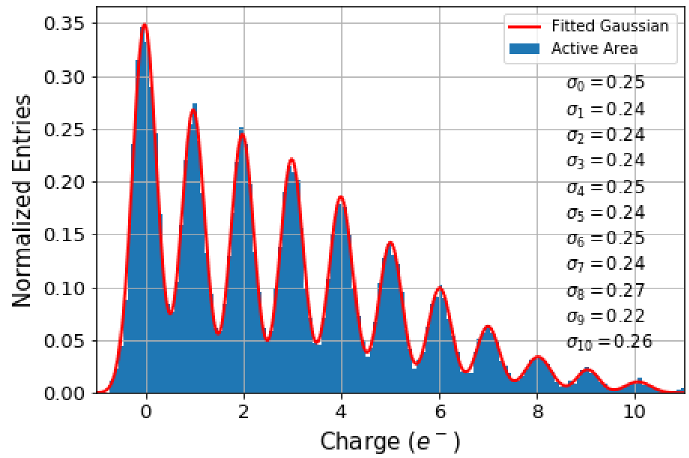

Figure 11: Single-electron charge resolution using a Skipper CCD with 200 samples per pixel. The measured charge per pixel is shown for pixels with low-light level illumination.

Smart Skipping

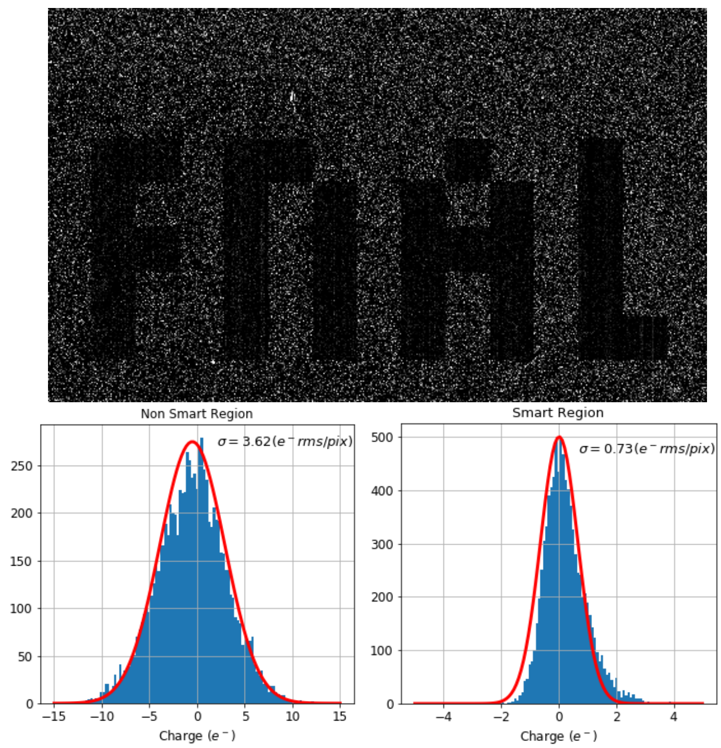

Figure 12: Smart Skipper image with FNAL pattern, demonstrating the targeted readout capabilities of Skipper CCDs.

A notable feature of Skipper CCDs is their ability to perform targeted readouts of custom regions of the CCD. This allows for faster readout strategies while still achieving low readout noise. To demonstrate this feature, in

Figure 12 we produced the following smart pattern (FNAL), where the smart regions contain 100 samples per pixel. A plot of the pixel value distribution for both the smart and non-smart regions show the low readout noise achieved by the smart skipper region. In the non-smart region, we see a rms noise of 3.62 e^- rms/pix while the smart region has a rms noise of only 0.72 e^- rms/pix.

APPLICATIONS

Skipper CCDs have the potential to usher in a new era of precision astronomy and cosmology. There are a number of applications for which Skipper CCDs are the ideal form of detector with its low read noise and targeted readout capabilities.

The **Λ**CDM (Lambda cold dark matter) model is a parametrization of the Big Bang cosmological model. Experimental tests of **Λ**CDM require the precise measurement of large samples of faint and/or distant astronomical systems. Spectroscopy is used to measure the doppler shift in elemental spectral lines of objects in motion. Light from faint astronomical sources is dispersed by spectrographs, resulting in low signal-to-noise in each detector pixel. In this regime, the efficiency and sensitivity of cosmic surveys depend heavily on detector readout noise. Reduced readout noise will be an important component of future spectroscopic surveys, which will have the potential to search for deviations in **Λ**CDM caused by warm dark matter particles with masses >30 keV [6].

The development of Skipper CCDs for astronomical applications is expected to have a large impact beyond cosmology. Astronomers choose from a limited set of observational parameters: sky location, wavelength range, spectral resolution, and exposure time. Skipper CCDs would add “instrumental noise” to the list of dynamically configurable quantities. An observer could optimize between instrumental noise and readout time to reduce the total time for any specific observation. Skipper CCDs will allow astronomers to get the most out of every photon when targeting faint object such as extrasolar planets [7].

There a many more applications for this next generation detector, giving Skipper CCDs a competitive advantage over conventional CCDs. We boldly suggest that every CCD used for astronomical or cosmological observations should be a Skipper CCD.

CONCLUSION

In summary, my work on this project comprised the mechanical setup of our testing station and the development of characterization scripts for the Astro Skipper CCD. We have shown that single-electron resolution is possible with a rms noise of 0.24 e^- rms/pix. We also demonstrated the targeted readout capabilities of Skipper CCDs and the potential applications this technique affords. The next immediate steps for this project include performing absolute quantum efficiency measurements as well as developing a robust method for targeted readout image correction.

Acknowledgements

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REFERENCES

[1] Ryden, Barbara. *Introduction to Cosmology*. Pearson, 2014.

[2] Proceedings of the National Academy of Sciences Jan 2004, 101 (1) 8-13; DOI:10.1073/pnas.2536799100

[3] https://www.darkenergysurvey.org/the-des-project/instrument/the-camera/

[4] "1.1 Scientific CCD History." *Scientific Charge Coupled Devices*, by J. Janesick, Spie Press, Washington, 2001.

[5] Tiffenberg, Javier, et al. "Single-Electron and Single-Photon Sensitivity with a Silicon Skipper CCD." *Physical Review Letters*, vol. 119, no. 13, 2017, doi:10.1103/physrevlett.119.131802.

[6] Dodelson et al. "Cosmic Visions Dark Energy: Science" (2016a) arXiv:1604.07626; Dodelson et al. "Cosmic Visions Dark Energy: Technology" (2016b) arXiv:1604.07821

[7] Crill & Siegler "EXOPLANET EXPLORATION PROGRAM: Technology Plan Appendix 2017" JPL Document D-98883 (2017)