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Improving Photometry and Astrophotography by Eliminating Dark Frames and Flat Fields

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University of New Hampshire, Durham

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Improving Photometry and Astrophotography by Eliminating Dark Frames and Flat Fields

Tom Ireland

Advisors: Dr. James Ryan, Prof. John Gianforte & Dr. Shawna Hollen

University of New Hampshire

Department of Physics – Undergraduate Thesis

May 15, 2019

Commented [JR1]: Tom, the scope and the topic are just fine for the thesis. The thesis needs more organization and some improved writing. It should be understandable by someone with a degree in physics, not necessarily astronomy. Much of the discussion is about poorly or undefined aspects of the problem. The vignetting is poorly described and the dark vs. light business is pretty loosy goosey. I am not sure how it works after reading this. Tell us how the corrections are made. Does the software "threshold" the counts in the camera ,subtracting a fixed value from every pixel to reduce the noise level. How does the vignetting correction go? Do you have an optics book to refer to for this? Basically there are more light ray paths through the instrument on axis compared to off axis. Do you amplify or diminish the signals in each pixel according to where they are on the CCD and some mask that you generate from the light box?

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Abstract

I report on the efforts to improve the dark frames and flat fielding procedure for the charged-coupled device (CCD) camera for the Celestron C14 telescope at the UNH observatory. Dark frames are images taken while the shutter of the camera is closed so that only electronic and dark noise and other internal inconsistencies are ~~captured~~recorded. These are important because they allow astronomers to subtract out interference ~~caused~~ from dark current. Additionally, flat fields are ~~pictures~~ images ~~that illuminate~~of the entire field of the telescope so that the brightness in the pixels of the telescope's ~~photos can be equally strong~~field of view is uni~~t~~form. Flat fields are vital since they provide a consistent illumination for all photos taken from the camera. With the combination of these two features, I was able to optimize the clarity of the telescope's ~~pictures~~ images and show through photometry how the new calibrated images appear in comparison to images prior to the calibration. Overall, these enhanced photographs will assist in achieving better results for future astronomy labs at UNH.

I. Background

There are many variable and transient objects in the sky. These include comets, planets, asteroids, variable stars, nova and supernova explosions. One type of object of interest is exoplanets. Exoplanets are planets that orbit a star other than our Sun. In other words, they are planets outside of our solar system. Just as the planets in our solar system show different attributes depending on their distance from the Sun, exoplanets also display many unique features depending on their relation to their parent star. The qualities of these exoplanets vary from massive gas giants with icy, rocky cores to smaller sized planets with hostile atmospheres. The main purpose of studying exoplanets is to search for Earth sized objects that lie in the 'habitable zone' of their parent star. This habitable zone is defined as the range of orbits that have a temperature that allows liquid water to form on the planet. If exoplanets with this crucial quality are found, they could be potential candidates for finding extraterrestrial life or even a future home for humans to colonize. So far, over four ~~thousand~~thousands~~s~~ of these exoplanets have been discovered and more and more are added to the catalog of exoplanets every day. [1]

There are multiple methods to search for exoplanets such as microlensing, radial velocity, astrometry, or transit photometry. While each of these methods has ~~its~~ advantages and drawbacks, the transit ~~photometry~~ technique is generally used most often. This method observes the ~~dip~~ drop in brightness that occurs as the exoplanet passes in between its parent star and the observer. This phenomenon is depicted in *Diagram 1* below. As the transit ~~processes~~proceeds, the planet ~~causes a shadow~~partially occults ~~in front of its~~the parent star and thus decreases the intensity of light that we see. This fluctuation in brightness is directly proportional to the size of the exoplanet so with this data we can accurately determine the exoplanet's diameter. Additionally, if you combine the transit ~~photometry~~ method with the radial velocity method, it is possible to uncover further information about the exoplanet like its mass and density~~,~~. These are crucial aspects to uncovering the nature and atmosphere of the exoplanet, which will then determine whether the planet is habitable or not~~,~~. The radial velocity method utilizes the fact that a star does not remain completely stationary when it is orbited by a planet~~,~~. It subtly ~~moves, ever so slightly, moves~~ travels ~~very subtly~~ in a small circle or ellipse, ~~responding~~ due to the gravitational ~~tug~~ pull of its ~~smaller~~ less massive companion~~,~~. When ~~viewed~~ monitored from a distance, these ~~slight~~ tiny movements affect the star's ~~normal~~ regular light spectrum~~, or color signature.~~. If the star is moving towards the observer, then its spectrum would appear slightly shifted towards the blue; if it is moving away, it will be shifted towards the red~~,~~. [2]

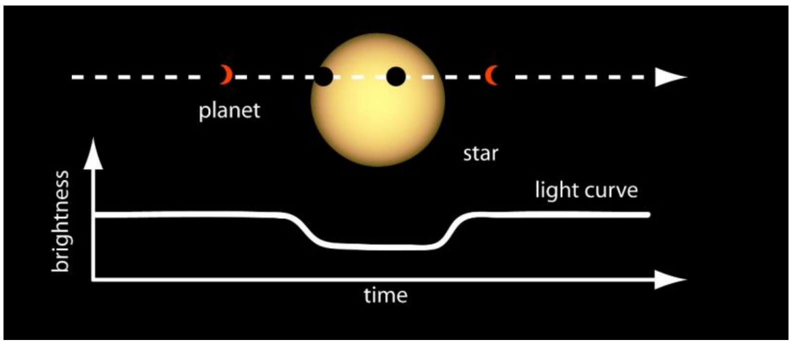

Diagram 1

It is clear to see the ~~dip~~ change in brightness of the parent star as the exoplanet passes in front

~~In order t~~To achieve the best results f~~o~~rom ~~the transit~~ photometry, one must capture the clearest ~~and most accurate~~ images of the exoplanet's transit~~,~~. The quality of these images can be diminished by many different ~~types~~ sources of error~~,~~. Some ~~sources of~~ interference come from the camera and others from the telescope~~,~~. These blemishes cause the data from photometry to be ~~inaccurate~~ noisy and sometimes useless~~,~~. To ~~eliminate~~ mitigate these sources of error, one must understand the layers of a raw image ~~and eradicate the aspects that interrupt~~ that produces good data collection~~,~~. The main components of an image consist of a light frame, dark frame, flat frame and bias frame~~,~~.

Light frames contain the actual image data of the object you are photographing with all the imperfections layered on top ~~of one another~~~~,~~. If the image taken is of a single, stationary object, then stacking itself or averaging the images could diminish the random noise in the light frames~~,~~. However, in the case of observing a transit, it is vital to eliminate as much noise as possible, since each image of the transit will need to go through the photometry process~~,~~. Some sources of error include: dark current, vignetting, dust, and hot pixels~~,~~. Solving these issues ~~is the responsibility of~~ requires dealing with the dark, flat, and bias frames~~,~~. After calibrating the light frames, they can undergo photometry and supply clean, useful data to create an accurate light curve for the planet's transit~~,~~.

[illegible] Dark frames are images taken while the cap of the telescope ~~is~~ cover~~s~~ing the aperture~~, so no light can get in.~~. This results in a

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picture of what ~~nothingness~~ pure darkness or nothingness should appear like. However, dark frames are not ~~nothing~~empty; they contain ~~the~~ both “cold” and “hot~~hot~~” pixels, thermal ~~signal~~fluctuations, and any other ~~signal that appears in the image~~instrumental artifact. Every pixel on the camera is unique in that they do not all record the signal equally. Some pixels are more active than others, which causes a non-uniform distribution of the incoming signal. Hot pixels have excessive charge and cause more noise, while cold pixels are those that do not respond as effectively.~~Therefore, the images can be zeroed by withdrawing the darks from the lights.~~ When thinking about all these frames, it is helpful to think of light frames as having layers of noise or interference. These layers correlate to dark and flat frames, which can be taken out so only a corrected light frame remains. Stacking darks is just as useful as stacking raw images because it ensures all the random noise from the CCD ~~camera~~ is ~~accounted~~averaged out ~~for in~~by the master dark frame. This master dark is essentially a collection ~~n average~~ of all the dark frames ~~and it will~~~~to~~that will be subtracted from the light images. It is crucial that the darks are captured at the same camera temperature as the lights since the thermal signal is dependent on temperature. It is therefore important that there is no temperature change between the times for acquiring the dark images and observing the target star. Additionally, they should have the same exposure length so that the darks contain the same noise duration that would appear in the light frames. ~~and International Organization of Standardization (ISO).~~

Flat fields are similar to darks in that they also help to normalize the lights, however, the blemishes that flats correct are from optical imperfections from the telescope instead of the CCD ~~camera~~electronics. Most telescopes fail at creating an even illumination across the camera sensor. Because of this, the images appear brighter in the center and darker around the edges. This phenomenon is known as vignetting and is a common issue in astrophotography. Moreover, there are often dust particles on the optical path that cause blotches known as ‘dust-donuts.’ Flat fields are taken to demonstrate what consistent brightness should look like. These are then averaged so that a master flat field can be applied to the light frames in the same way as the master dark. Flats need to be taken with the same focus, camera orientation, and optical setup as the lights so that the same conditions are met. There are many ways to take flats such as using the evening sky, a light box, or pointing the telescope at a white computer screen. This is an effect of the optics of the telescope and does not vary between observations or with temperature.

Finally, bias frames are used to extract the readout signal from the camera sensor. Although not every pixel receives a signal on each image, there is always a change in how the sensor translates data. Bias frames can be subtracted from your lights, darks, and flats to adjust for this variation. To attain the bias signal, p~~p~~ictures need to be taken as close to zero exposure length as possible and with the lens cap on; however, ~~.~~ t~~T~~he temperature of the camera is irrelevant for bias frames~~, but they should be performed under the same ISO~~. However, since dark frames also contain the bias signal, it would be superfluous to capture bias frames for this procedure. All these different frames contribute to the final corrected image that will be used to extract data. *Figures 1-4* below show examples of a light, dark, flat and corrected image. [3] [4]

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Figure 1

To the left is an example of a raw image taken of a star cluster before any calibration has occurred.

To the right is the ~~respective~~ corresponding dark frame ~~for the original image~~.

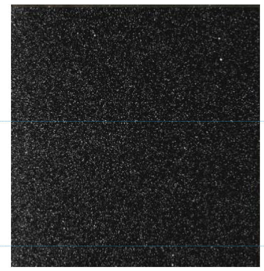

Figure 2

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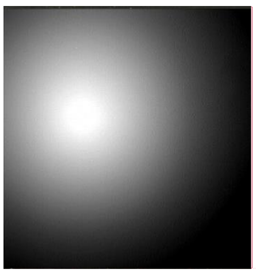

Figure 3

The image on the left shows the vignetting that can occur from the uneven lighting of the telescope.

On the right we see the final corrected image of this star cluster.

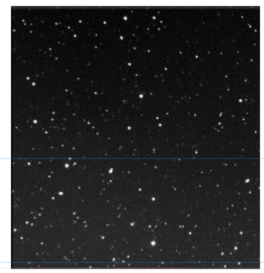

Figure 4

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II. Introduction

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This project was performed to benefit future astrophysics students at UNH by improving the results of the exoplanet transit lab and any future research or labs involving the UNH telescope. This goal was met by fine tuning the calibration process for the CCD camera and telescope. The exoplanet lab's purpose was to achieve a light curve for an exoplanet's parent star like the curve in *Diagram 1*. By adding the calibration steps, the lab is built upon further and provides insight that would otherwise be inaccessible. This procedure can be applied to most cameras; however, the dark frames and flat fields must be specified to the same conditions as the light frames. Calibration is vital whenever scientific instruments are being used and for this case the improved images from the telescope will provide better data. The data drawn from these images in the case of an exoplanet transit consists of the photon strength in each passing image. Sometimes though just a clearer picture is the only goal for the avid star gazer.

This report includes instructions on how to take successful dark and flat frames, how to average these into a master dark and master flat, and how to apply these tools to light frames. Unfortunately, due to time constraints and weather, neither an exoplanet transit nor a star cluster could be observed. While this restricts physical findings from the lab, the theory and practice of this calibration process can still be discussed and explained with alternative evidence. It is important to understand that the scope of this procedure is not limited to exoplanet transits, but it extends to any and all images taken on the UNH telescope.

The equipment and methods used in this project are laid out in the following sections. Though the tools used here are unique to the UNH observatory, the calibration process with dark and flat frames can be utilized for any telescope and camera if the specific conditions are met for different equipment. Additionally, as previously mentioned, there are numerous ways to capture flat fields and each has individual advantages and disadvantages. The initial darks and flats will not always come out ~~beautiful~~ as expected because there are many external factors that can influence the quality of the images. If the dark frames are not taken in complete obscurity, they could appear tainted and become unusable. Similarly, if the flats are captured under a cloudy sky or ~~poor~~ uneven illumination, they will not collect all the blemishes ~~on~~ in the optical path~~telescope lens~~. While it is possible for these issues to occur, normally the procedure is smooth and usually only the flat fields require a little extra troubleshooting.

Additionally, it is beneficial to mention that my peer Anthony Cappuccio is working with the telescope and its autoguiding feature. This other tool will ensure a smooth tracking of whatever object is being observed in the sky. This autoguider can be controlled through the autoguider tab on the SkyX page. By combining the calibration and ~~his~~ the autoguider, the likelihood of attaining ~~good~~ high quality images is increased immensely.

III. Experimental & Methods

This experiment was performed at the UNH observatory with the use of its Celestron C14 telescope and CCD camera. The dark frames could be taken at any time of day, since they are performed while ~~the cap of the telescope is on~~aperture of the telescope is covered by camera shutter. The flat fields, however, needed to be acquired in a well-lit environment so either a dawn or dusk setting should be applied. Another option for flat fields is to use artificial illumination such as a light box. Moreover, the application SkyX was used to control the telescope and camera, and FITS Liberator was used to analyze the captured images. Pictures of the programs and equipment can be seen below in *Figures 5-10*.

Figure 5

The UNH observatory is in an isolated area to avoid light pollution and to provide access to the open sky.

The charged-coupled device camera is mounted on the telescope where an eye piece would normally be located.

Figure 6

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Before taking any dark or flats, one should review the SkyX program and become familiar with its capabilities. The taskbar for SkyX is easy to navigate and has many useful tools relatively easy to follow and has interesting tools to test out. The first few features merely control the direction that the sky view looks towards such as North or South. The most important area to understand is the tabs that display the camera and telescope. The telescope page has options to find an object in the sky and slew the telescope to that object, to flip the telescope and its counterweight, and to park the telescope. These are the most common maneuvers for the telescope. It is vital to park the telescope before finishing your work in the observatory to maintain a strong mount and to avoid any stress to other components from the weight of the telescope.

The camera page is displayed in *Figure 7*. It has details on exposure time, frame type, and camera temperature. Before taking any photos, the temperature of the camera should be set. The lower the temperature of the camera, the less noise is created from the CCD and thus better-quality images can be captured. Moreover, there are options to take images either as continuous series or one at a time. These choices should be utilized for different situations. For instance, it makes sense to take continuous images of a transit and to take individual photos to fix focusing issues or to synchronize the telescope with the actual sky. The camera page is also where you would select a save file for all the images. Having a unique file name for each set of photos is crucial in organization. Start by creating a folder labeled with the date of observation and then identify each group of photos by the type of image and its exposure time.

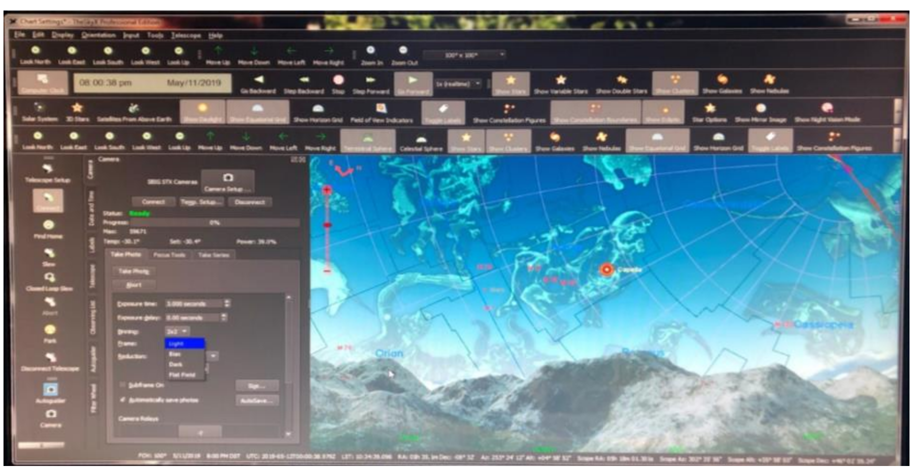

Figure 7

This snapshot of the SkyX program shows the various maneuvers and features that the telescope and camera can perform. It also provides a projection of the part of the sky the telescope is aimed at and the stars in that area. Finally, there is a drop-down menu that allows the user to choose which frame they want to capture.

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To capture the dark frames, the temperature for the CCD camera was set to -30˚C, which is the same temperature that the light frames would be taken. Next, multiple series of dark frames were taken to ensure there was a matching master dark frame for different exposure times. Overall, three series of 10 dark frames were created with exposure times of 30 seconds, 30 seconds, and 45 seconds. The first two series have the same exposure time because they were taken on different days and I wanted to observe any possible differences due to atmospheric conditions like external temperature. The temperature around the camera affects how much power the camera needs to use to cool itself. Therefore, the difference in power may result in unique dark current patterns. In general, these differences are negligible but are important to remember if the telescope is being used at different times of the year. The darks' exposure times correlate to the most common exposure times of light frames. Sometimes it takes more than 30 seconds to capture a successful light frame so a series of darks with a 45 second exposure time was also recorded. Each of these series was averaged into a master dark frame. It is very common for astronomers to have catalogs of numerous master dark frames taken under unique conditions so that they can apply them to future light frames of the same conditions. Each of these master darks has a thermal count across its pixels and this count is what we wish to subtract from the light frames.

Flat fields are more ~~tedious~~ difficult to capture than darks but there are multiple ways to take them. The~~Firstly, the~~ most important factor to remember is that the focus settings are the same as they would be for the light frames; otherwise, the blemishes will not appear as they do on the light frames and their subtraction would not help. The method used in this lab to take flat fields was to tightly secure a white T-shirt over the aperture of the telescope to diffuse light and then face the telescope towards the evening sky for even illumination. This took numerous attempts and was the most troublesome aspect of this experiment. For some reason, many of the flats returned as static images and appeared more like a dark frame than a flat field. Initially I had thought that this was due to cloudy skies, but even under perfect conditions some of these flats came out poorly. The fundamental variable to achieving a good flat field was found to be its exposure time. First, the exposure time was set to 10 and 8 seconds for two different series, however, these proved to be too long and resulted in unusable images. After troubleshooting for some time, with help from Prof. Gianforte I decided to change the exposure time to 3 seconds and eventually took three series of 10 flat fields with exposure times of 3, 1 and 0.5 seconds. The lowered exposure time allowed less light to overwhelm the image and only highlighted the optical issues. Finally, a master flat field was made for each series and the clearest one would be used to calibrate the light frames.

Figure 8

In both figures we have the Celestron C14 telescope. On the left it is setup for acquiring flat fields and the white T-shirt is used to diffuse incoming light. In *Figure 9* the telescope is prepared to capture dark frames; however, before they were taken, the door to the observatory was closed to stop light from entering.

Figure 9

The FITS Liberator application is not heavily utilized in this lab. Essentially it is used simply to analyze the images taken by the telescope and decide if they are usable. The main feature for this program is the histogram which has sliders to adjust the white and black input. This allows for contrast in the image, so it can be studied further. This is another situation where organization is important because to open the app you must select an image from a folder to examine. Therefore, organization is a good trait to have as an astronomer so that all the extensive files do not get cluttered or confused. Overall, FITS Liberator is a simple tool to help deduce the good images from the bad ones.

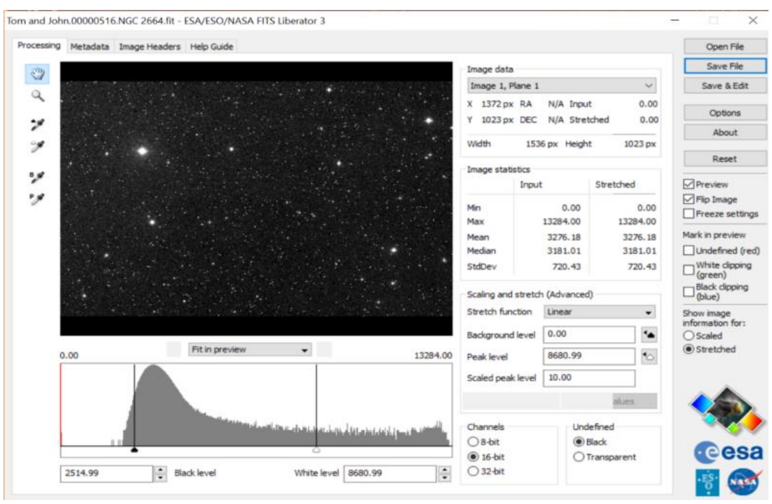

Figure 10

Here we see a preview of a star cluster and its corresponding histogram below it. The sliders on the histogram affect the black and white levels of the image and therefore provide contrast so specific features of the photo can be observed more easily.

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Although this research was impeded by weather, the following steps would have been taken in order to finish the calibration process. Once the user has a master dark and master flat to apply to their light frames, they would choose an exoplanet such as CoRoT-2 b or a star cluster like M3 to observe. This step is essentially the bulk of the exoplanet transit lab that is performed in PHYS 705.02 so I will not go into extreme detail. Transits of exoplanets can take hours to transpire and it is important to record the ingress and egress, so the resulting light curve can be compared to the standard brightness of the parent star. Regardless of the object being tracked in the sky, the astronomer must make sure it lands in the telescope's field of view or else it will not show up in the captured images. This can be an issue sometimes if the telescope is not properly synchronized with the SkyX program. Sometimes you must analyze patterns in star clusters to identify the object in question. The final step after all the necessary light frames are collected is to apply the master dark and master flat to them so that all the optical and internal interference can be subtracted. This should result in clear final pictures and if they are of an exoplanet transit, then they can undergo the photometry process to achieve a light curve.

IV. Results

The following section contains the outcome to the dark frames and flat fields. *Figures 10-11* show examples of the dark and flat frames that were recorded. Just as in the samples from the Background section, the dark frame contains the different thermal signals of each pixel and the flat field displays vignetting and dust-donuts.

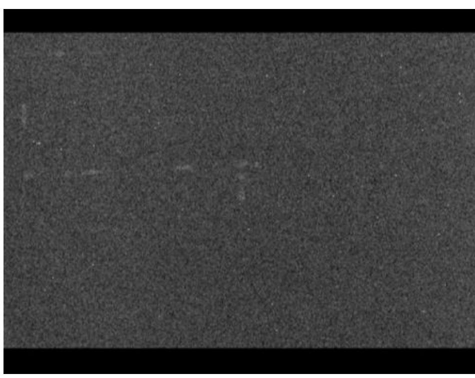

Figure 10

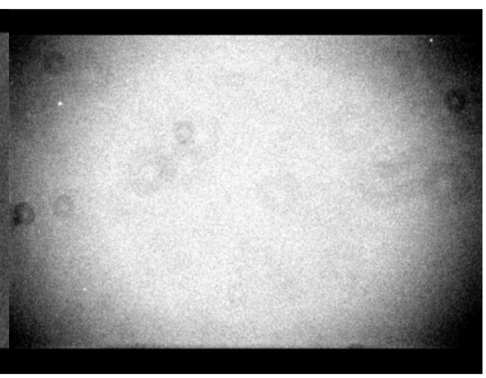

Figure 11

In *Diagrams 2-3*, there are two light curves that were pulled from the ETD and recorded by other astronomers. Since I was unable to gather enough data to perform photometry, these light curves will act as examples. Without calibrating the light frames, the data collected from imperfect images would be scattered and appear like *Diagram 2*. While it is helpful to upload any and all information on an exoplanet, scientists prefer to have the most accurate data possible, so they can use it to make real applications or construct plans based on trusting evidence. Therefore, *Diagram 3* offers a better alternative. The smooth light curve with precise data points is much more useful to astronomers, which is why calibrating is crucial.

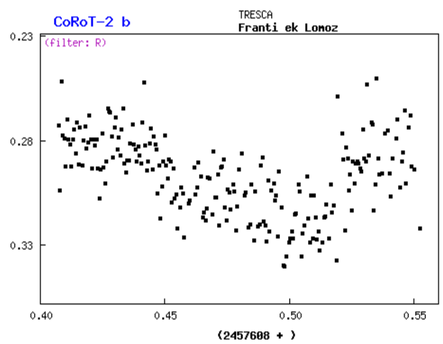

Diagram 2

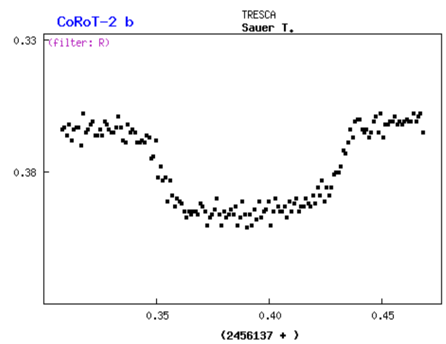

Diagram 3

V. Conclusion

In conclusion, dark frames help astronomers eliminate the inherent noise from the charged-coupled device electronics and flat fields ~~impact the success of astrophotography immensely.~~ provide an even illumination to avoid blemishes on the optical path. The ~~purpose~~ reason ~~of~~ for ~~producing~~ taking dark or thermal count images is to subtract the ~~contribution~~input from thermally generated charge in the image. Flat fielding corresponds to correcting the combined optical-system and CCD throughput at each pixel so that each pixel on the CCD would respond equally to a source with the same photon flux. Flat fielding ~~removes~~ relieves the negative ~~effect~~ influence of the pixel-to-pixel sensitivity variations ~~across~~ throughout the array as well as the effect of [illegible]

By averaging the captured darks and flats, one can create master darks and master flats. These are the frames that were removed from the light frames to produce a corrected image that only contains the data collected from the sky. The object being photographed is irrelevant because the calibration can be applied to any image. Clear images are the goal for any astronomer, though it is not a simple task to accomplish. The resulting corrected images are not only often beautiful to look at but they can also lead to astounding scientific discoveries.

Though I failed to produce my own evidence because of poor weather conditions (a common issue in New England), astronomers across the globe utilize the dark and flat frame~~is~~ calibration method to improve their images. It is a powerful tool and will continue~~d~~ to be applied to photography in all forms so long as cameras produce interference and dust produces dust-donuts.

[1] Howell, Elizabeth. “Exoplanets: Worlds Beyond Our Solar System.” *Space.com*, Space, 30 Mar. 2018, www.space.com/17738-exoplanets.html.

[2] “Transit Photometry.” *The Planetary Society Blog*, www.planetary.org/explore/space-topics/exoplanets/transit-photometry.html.

[3] “The Types of Images.” *Raw Astrophotography Data*, www.rawastrodata.com/pages/typesofimages.html.

[4] *Durham University Community*, community.dur.ac.uk/physics.astrolab/flat_fielding.html.

~~[4]~~[5] “Applying Flat Field and Dark Frame Corrections.” *Flat Field and Dark Frame Correction*, www.cfht.hawaii.edu/~baril/Pyxis/Help/flatdarkfield.html.