Data Reduction Script for Kilodegree Extremely Little Telescope Transit Survey

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ABSTRACT

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Transiting planets can be discovered through the method of photometry. The Kilodegree Extremely Little Telescope (KELT) Transit Survey team is a collaborative effort to discover more transiting planets. Image Reduction and Analysis Facility (IRAF) has been used to create a script to efficiently pipeline the night sky's raw images into processed ones to prepare them for photometric measurements. The details to the structure and reliability of the data reduction script are outlined. The photometric results are sent back to the KELT team. Discussion of the significance of the light curve is also detailed.

ACKNOWLEDGMENTS

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Chapter 1

Introduction

The study of exoplanets can be achieved through photometry. Photometry is a measurement of flux or the change in light. Some exoplanets transit their host star which makes the method of photometry ideal for the study of these extraterrestrial planets. Photometry requires that the raw images taken by the telescope of the exoplanet be data reduced. A data reduction method is discussed and a script is made to prepare the raw images for photometry. Accurate light curves can then be made with photometric computer programs. The study of exoplanets is a collaborative effort.

1.1 Transiting Planets

The search for exoplanets has gained momentum in the past years. Exoplanets are planets far from our solar system in orbit of their own sun. Some exoplanets can be observed through the method of photometry. These exoplanets are also referred to as transiting planets. Photometry is a measurement of light, and when the exoplanet transits, i.e., crosses in front of its star, the light observed by a telescope dips in brightness. This is defined as a light curve, and for transiting planets the dip in flux is small as seen in Figure 1.1. Detection of a light curve signifies a high probability that a transiting planet exists.
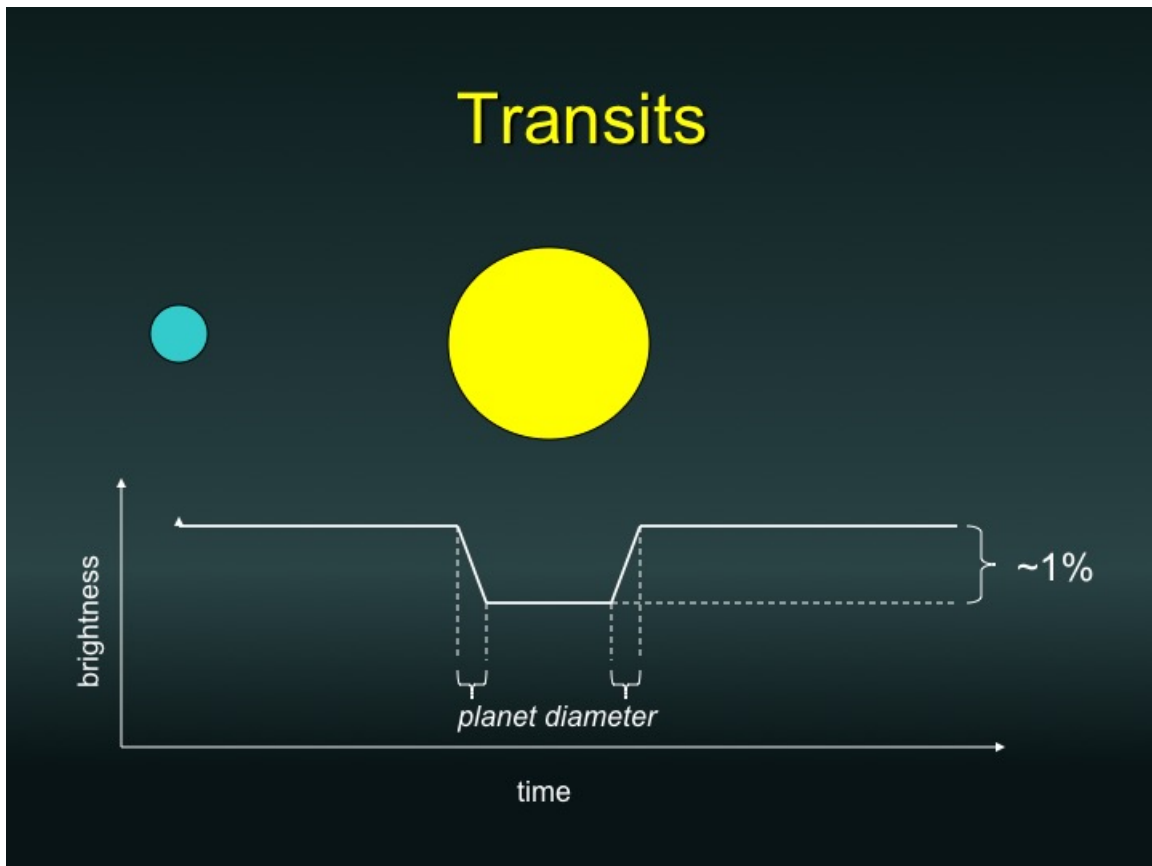
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Figure 1.1 Light curve of a transiting planet in orbit of its host star. The time at which the transit occurs is the ingress. The transit ends at the time of the egress. This eclipse causes a dip in the measured light from the star. This is one way to detect exoplanets. It also leads to future studies into properties of the exoplanet. Figure is provided by Dr. Denise Stephens.

The light curve of a transiting planet is fairly simple. The observed brightness of the host star dips for the time the transiting planet crosses it. The commencement of the transit is known as the ingress, while the end is known as the egress. The importance of the ingress and egress are shown in Figure 1.1, where the initial dip in light allows astronomers to calculate the diameter of the transiting planet. Continuous study of the light curve occurs since the transiting planet orbits its host star periodically. However, the vastness of space makes it difficult to study transiting planets alone.

To study the infinity that is space, astronomers form teams to study celestial objects en masse. The Kilodegree Extremely Little Telescope (KELT) Transit Survey Team consists of private observatories, amateur astronomers and several universities including Brigham Young University (BYU). The KELT team is found all over the world as seen in Figure 1.2. The purpose of the KELT team is to efficiently identify more transiting planets on a continuous basis. This is possible because the two KELT telescopes scan the night sky for periodic variations in brightness of the stars. When an object has been identified by the KELT telescopes as potentially hosting a transiting planet, the data collected is sent out to the entire team to further study candidate transiting planets. This process will be further highlighted in Section 2.1.

The effectiveness of the KELT team lies in the communication between team members. Not all variations in brightness detected by the KELT telescopes are transiting planets. To efficiently study transiting planets, the the turn around time, the time from when the KELT team, including BYU's astronomy department, is notified of a possible transiting candidate to when they return their individual findings needs to be as short as possible. The turn around time includes reducing the data and making a light curve. An immediate and reliable turn around time allows the KELT team to focus more resources on the discovery of more transiting planets. A light curve is made from processed images of the night. One way to decrease the turn around time is to streamline the raw images into processed ones, thus shortening the time it takes to get images ready for

Figure 1.2 The red circles are the locations of the two KELT telescopes. The KELT telescopes scan the night sky as a whole, looking for variation in brightness. The blue pinpoints denote the locations of the team. The 40+ telescopes of the team observe the night sky by collecting images of a specific object. The map is from the KELT team.

photometry.

1.2   Astronomy Computer Programs

There are several programs through which raw images can be data reduced. Image Reduction and Analysis Facility (IRAF) (Tody 1986) has been a reliable program in the astronomy field for years. The advantage to using IRAF is its ability to be transformed into a variety of programs. This is due to the many packages that are a part of the program. The IRAF program can be installed with specific packages to facilitate the data reduction process of astronomy raw images pertaining to many different projects.

   A data reduction (DR) script has been created in IRAF. Scripts in IRAF can access other packages in IRAF as well as the option to run as background programs. The background option allows scripts to continue running while the computer is unattended. The DR script allows for immediate

data reduction of the night's images and has also been made to be automatic with limited user interface. This is of great import as the data reduction process can take several hours. Also, because the DR script is automatic, the observer can rest while the data reduction process is underway. The customization and creation of the DR script is outlined in Chapter 2, with the source code in the Appendix.

The benefit to having the DR script is that the data can be processed without having to wait for the next command. More raw images increase the amount of time to complete the data reduction process and thus the wait time in between commands. The purpose of creating this specific DR script to perform the data reduction process has been to decrease waiting time, as the DR script jumps to the next command immediately. The DR script pipelines the data from raw images to processed images in a reduced amount of time compared to data reducing by hand. The processed images are then used for photometry programs. The intent is that with this DR script the raw images gathered for the KELT team can be compiled into processed images, as the DR accounts for the known errors that impede the study of transiting planets in a shortened amount of time.

1.3 Data Reduction Process

Just as it is known that space is large, astronomers know that the sky is noisy. The noise from the sky can cause the photometric results to vary from what they should be or show false positives. Clouds can be a great annoyance as clouds block the view of the transiting planets. Also, clouds in the frame of the telescope view can negatively affect the data by reflecting light which will ultimately skew the light curve results in the photometric process. Clouds and light pollution pertain to the sky. Other issues that can give negative results to the raw images are the telescope and the camera attached to it.

The lens of the telescope serves as the most important part in observation of the night sky. The

lens gathers all the light that has traveled for years to reach Earth and pinpoints it to a discernible portion observed and recorded on the camera. However, the lens has a few inherent problems. A big concern that has to be faced with each telescope is vignetting. The recorded raw images tend to be corrupt around the edges and this has to be taken into account later and resolved through the data reduction process created in the DR script.

The last variable to be aware of in observational astronomy is the camera. Because the information is compiled on a charge-coupled device (CCD) camera, the pixels are very sensitive. In actuality the CCD camera has to be kept at very cold temperatures to avoid collecting excess electrons when gathering data from the telescope. The cold temperature is an effective barrier against these electrons. The light coming in from the telescope is a different story. Excited electrons can interfere with what the camera should observe. Hot pixels on the CCD camera have a higher electron count than they should. Hot pixels have a linear relationship and are addressed in Section 2.6. The high counts from the hot pixels can make the star appear brighter than it is if the star crosses any hot pixel during the night. Bad pixels can also occur on the CCD camera. Bad pixels cannot be corrected as bad pixels pertain to both dead pixels-pixels that no longer work-and hot pixels. Bad pixels are resolved as described in Section 2.4 by being blocked out and given an average value from the pixels nearby. These variations have to be taken into account when reducing the raw images into neat processed ones that give a more accurate depiction of the night sky.

All of these factors add up to create noise in the raw images, extra information that can lead to incorrect results. The DR script resolves these issues to the best extent possible. The focus of this paper is to convey how the data reduction script was created for the BYU astronomy department to pipeline the data for preparation of photometry.

Chapter 2

Data Reduction Pipeline

Raw images for the data reduction pipeline are collected by the David Derrick Telescope (DDT). The DDT is a part of BYU's Orson Pratt Observatory. The raw images include zeros, darks, flats, filters and object frames; each of these will be further detailed. The raw images are gathered into a computer folder and from there they are run through the data reduction pipeline which makes corrections to the known instrumental errors as well as decreasing the turn around time to the KELT team. Access to the KELT team's Transit Finder helps prioritize which transiting planet to find and is discussed in section 2.1.

The DR script is linked to several other subscripts. The basics of IRAF are outlined in section 2.2. The headers of the raw images are discussed in section 2.3. The bad pixel mask document and trim subscript are detailed in section 2.4. The Master frames which include the Master Zero, Master Dark and Master Flat, as well as the filters used on the DDT are discussed in sections 2.(5-8). Finally the processed images are discussed in section 2.9; the processed images are then ready for photometry.
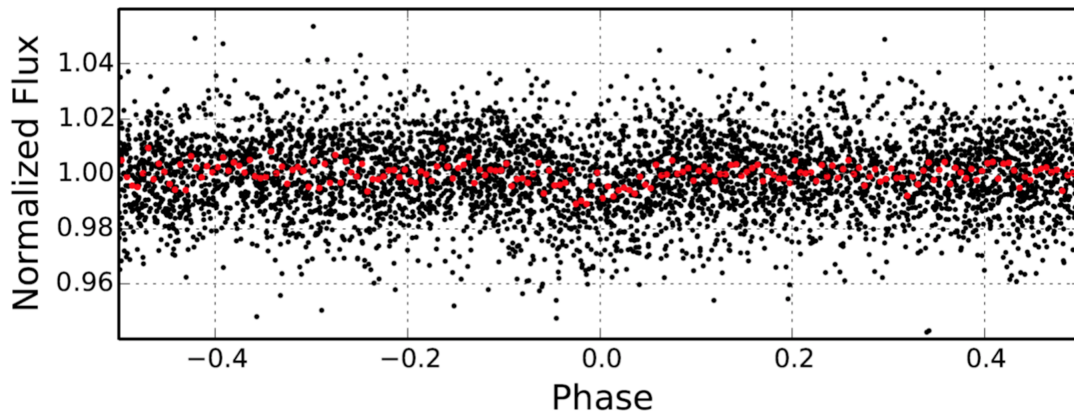
Figure 2.1 The observed light (black) is the collection of data over several years from KELT. A phase curve (red) has been fitted to the data as the data has been wrapped on itself over time. The phase curve indicates a possible transit (Oberst 2017).

2.1 KELT Transit Finder

The KELT Transit Finder permits observers to access the database of the compiled data from the two KELT telescopes. The KELT telescopes scan the night sky as a whole in strips and look for periodic variations in brightness. The KELT telescopes collect data over several years looking for possible periods in the data of the same object. A Fourier Transform is applied to the data collected from the KELT telescopes and possible results are what Figure 2.1 shows. A phase curve is applied to the data. If a dip in light results from the phase curve, then it means there is a possible transit. The KELT team observes the possible transits that the KELT telescopes find to see if they are real transits. Calculations are made from these phase diagrams like Figure 2.1 in regards to the estimated period, ingress and egress of the transiting planet. Other essential data to observe the transiting planet is also given from these calculations.

The KELT Transit Finder has been programmed to output several important pieces of information. The location of the host star is given by the right ascension (RA) and declination (Dec) which translates to longitude and latitude imposed on the sky. The start and end time of the potential transit are also included. All of these features can be seen in Table 2.1. It is important to get onto

Table 2.1 Data available on the KELT Transit Finder. The KELT observations are made by scanning the night sky in strips to locate possible transiting planet candidates. The KELT Transit Finder allows the search of the database of the past several months. The most important information columns from the KELT Transit Finder table are the Start-Mid-End times, Duration, RA & DEC and Period columns. The KELT Transit Finder is maintained and operated by Eric Jensen.

Local evening date	Name	V mag	Start— Mid —End	Duration	BJD_{TDB} start-mid-end	Elev. at start, mid, end	RA & Dec (J2000)	Period (days)	Depth (mmag)	Priority
Wed. 03-01-2017 (local) : Nautical twilight 02:17 - 12:59 (UTC)										
Wed. 03-01-2017 (local) Nautical twilight 02:17 - 12:59 (UTC)	KC20C21650 Finding charts: Annotated, SkyMap; Info: KELT page, Simbad, 2MASS; Airmass plot, ACP plan	11.15 Moon 14% @99°	19:42— 23:33 —03:24 ± 0:48	7:42	7814.321 7814.482 7814.642	15°, 29°, 53°	09:54:36.24 +64:36:45.3	1.44	2.6	5
Wed. 03-01-2017 (local) Nautical twilight 02:17 - 12:59 (UTC)	KS05C008737 Finding charts: Annotated, SkyMap; Info: KELT page, Simbad, 2MASS; Airmass plot, ACP plan	10.01 Moon 14% @76°	21:10— 00:15 —03:20 ± 0:43	6:10	7814.382 7814.510 7814.639	-8°, 25°, 43°	06:41:03.71 -06:42:58.8	2.57	3.77	35
Wed. 03-01-2017 (local) Nautical twilight 02:17 - 12:59 (UTC)	KC06C14786 Finding charts: Annotated, SkyMap; Info: KELT page, Simbad, 2MASS; Airmass plot, ACP plan	11.24 Moon 14% @105°	21:54— 00:16 —02:38 ± 2:13	4:45	7814.412 7814.511 7814.611	-2°, 22°, 49°	08:56:37.15 +26:14:54.4	7.07	16.80	5

the target star before the start time to catch the ingress of the transit-the time at which the eclipsing begins-and the dip in the light curve commences. The duration and period are also included in the database. The duration is how long the transit is expected to last and the period is how often the transit occurs. These calculations are made from a fast Fourier transform on the data collected by KELT.

2.2   Basics of IRAF

The IRAF program is a collection of various packages that a user can choose to implement. The IRAF language is based off of C++ and Fortran. The IRAF program is also taught at Brigham Young University in their Physics 329 class where it is used to reduce data from the DDT or West Mountain Observatory.

The advantage to IRAF is the accessibility it has to other packages as well as the ability to create scripts. The purpose of the DR script that was created in IRAF is to reduce turn around time back to the KELT team. The DR script achieves this by being a pipeline program that is automatic with limited user interface.

The DR script only requires a few initial parameters that are discussed in detail in the following sections. Each future section discusses its purpose as the DR script calls on each subscript consecutively and separately. The subscripts of the DR script contain commands to reduce the raw images in preparation for photometry.

2.3   Headers

Apart from observing the specific host star, the observer also uses the telescope to record different frames over the course of the night. These various frames have been mentioned in Chapter 1 and help eliminate the errors of the sky and telescope. Each of these frames is differentiated from the next by headers such as zero.fits, dark.fits, or flat.fits. These different allocations allow the computer to separate the images. Thus each image has a specific header to designate what it is.

The purpose of the header is to help IRAF identify the different frames. When tracking a transiting planet, the needed images are zeros, discussed in section 2.5; darks, discussed in section 2.6; flats, discussed in section 2.7; filters, discussed in section 2.8 and object, discussed in section 2.9. However, because of systematic reasons, these initial headers must be updated for IRAF to

register them. This is because IRAF requires that the word must be exact to register and update the header of the image. To allow a wider variety of research, the header script initializes everything first as an object. Once all the headers are updated to object, the headers are updated again to their specific category of zeros, darks, flats and the filters; their importance is illustrated in sections 2.5-8. Now that IRAF can easily read and access the headers of the images there is only one more step before the data reduction process begins.

2.4   Bad Pixel Mask and Trim

A bad pixel mask (BPM) is created and applied to every raw image to block out the bad pixels on the CCD camera. A BPM, as seen in Figure 2.2, was created for the DR script from the instructions found on eso.org. The BPM replaces the bad pixels as well as some of the hot pixels with an average of the nearby pixels. With the application of the BPM, the continuous flow of light, or flux, of the host star is less likely to be corrupted. The BPM should be updated frequently as the pixel precision of the CCD camera varies over time. Another error to address that deals with flux as well is vignetting.

The trim subscript of the DR script accounts for vignetting. The edges of the raw images don't have continuous flux. Photometry uses the measured flux to verify the candidate transiting planets. However, vignetting prevents an accurate measure as there is no flux at the edges for the photometric readings. Not having flux on the edges would be detrimental if the pixels are left in the data, as the dip in light is only one percent. This is why it is necessary for each raw image, including the zeros, darks, flats, filters and object to be trimmed. Each image is trimmed to be the same size. This small dip in light is also the reason to why applying the BPM is of importance. This is an instrumental error from the camera. The application of the BPM and trim subscript is shown in Figure 2.3. With these errors being taken out of the equation the next process can begin,
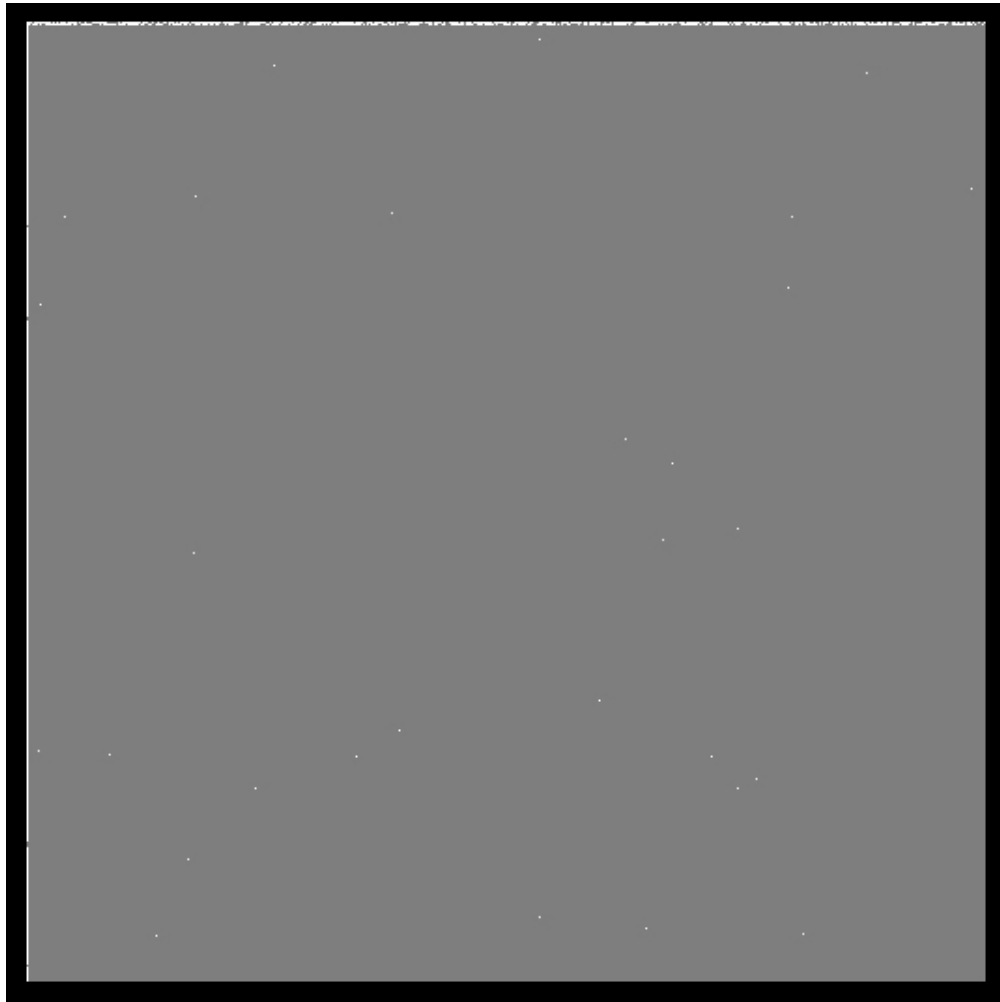
Figure 2.2 The bad pixel mask is made from flat field images with high and low counts. The bad pixel mask replaces bad pixels, which appear as the white specks in this image, with the average of the surrounding pixels when applied to the raw images. This gives an average of what the counts should be from the flux.
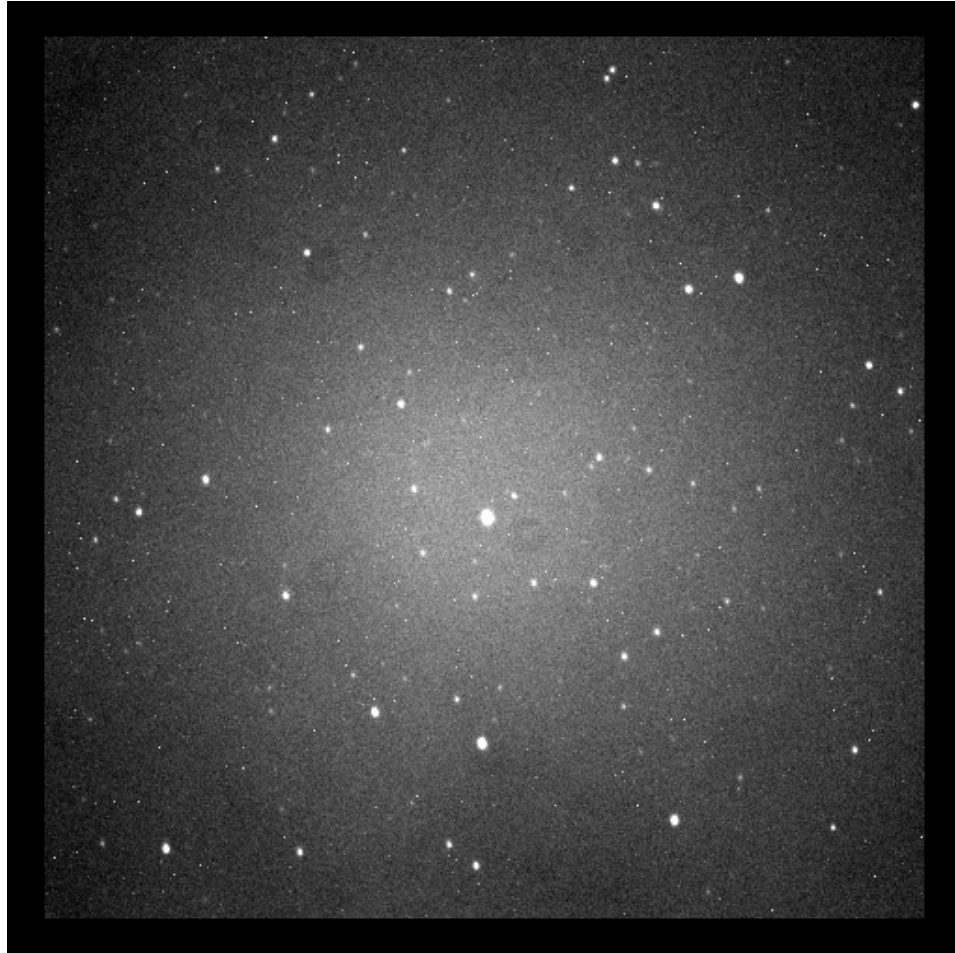
Figure 2.3 Trimming the images is helpful as it gets rid of vignetting. The BPM has already been applied to this image.
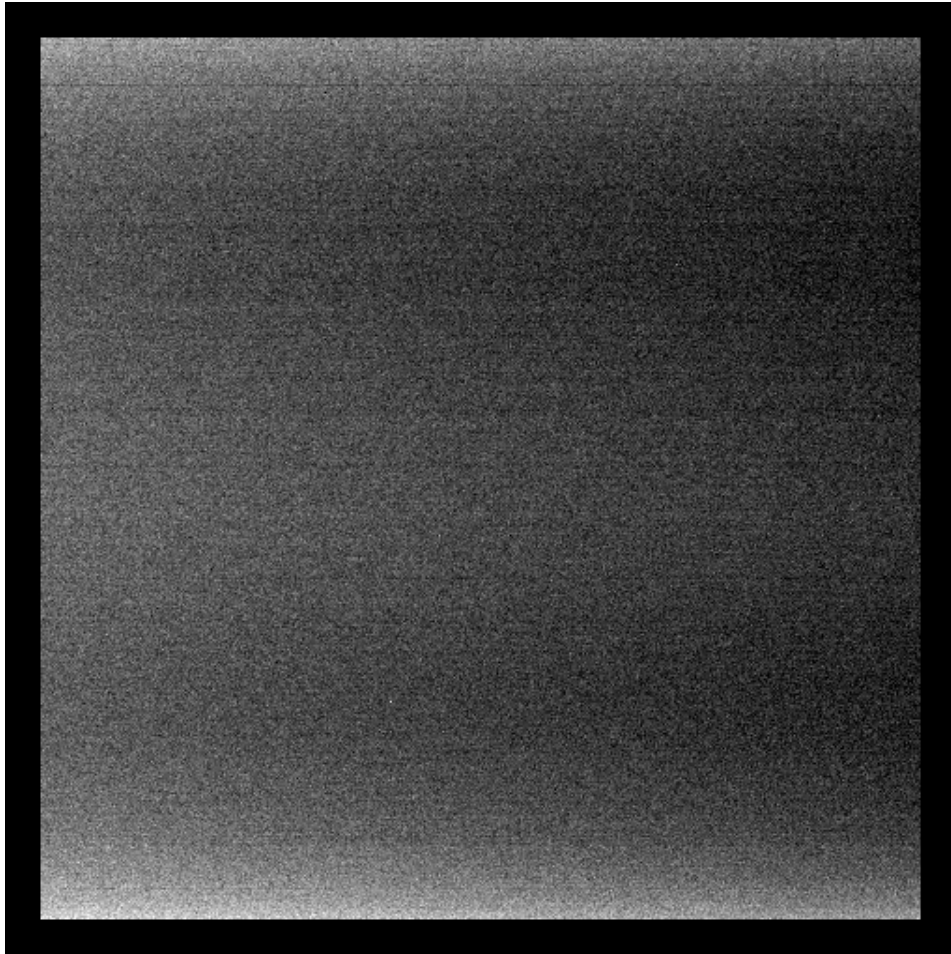
Figure 2.4 The Master Zero is the compiled data from the zero images. The Master Zero will be subtracted from the images that have already had the BPM applied and have been trimmed.

and that is creating a Master Zero.

2.5   Master Zero

Errors occur in IRAF when data is compiled with negative pixel values. To circumvent this a current is given to the camera to raise it to a bias of about 1000 counts. The data can be compiled in IRAF now without the worry of an error. However, once in IRAF, the bias needs to be removed
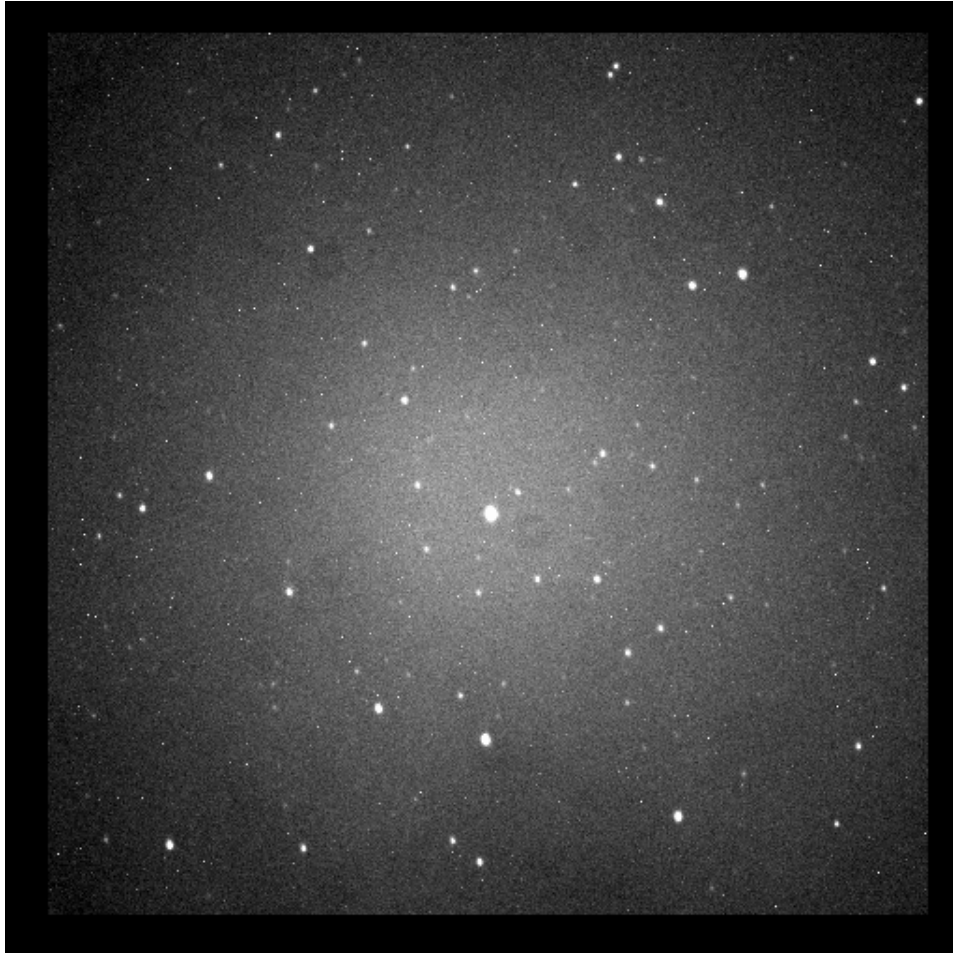
Figure 2.5 The Master Zero is subtracted from the image that has already had the application of the BPM and has been trimmed. The Master Zero essentially adjusts the pixel value.

so that the data can be accurate.

Zero images are taken to remove the bias frame. Zeros are taken while the shutter of the telescope is closed. There is no integration time or illumination associated with zero images. The DR script creates a Master Zero as seen in Figure 2.4 to be subtracted out of the raw images to restore the true pixel value to said images. The application of the Master Zero to the raw image can be seen in Figure 2.5. Now the known instrumental errors in regards to the integration time and illumination of the telescope can be addressed.

2.6 Master Dark

Another frustration faced in astronomy are electrons jumping the band gap of the CCD camera without being triggered by a photon. The results of electrons jumping are extra specks of "fake" light because of the increased count. Pixels that do this a lot are called hot pixels. To account for the electrons jumping the band gap without being triggered, dark frames are taken. Dark images count the electrons that jump without being excited. A Master Dark is shown in Figure 2.6. This process is dependent upon the integration time and seeks to resolve hot pixels. Integration time matters as faint host stars require more exposure time than a more luminous host star, thus increasing the amount of electrons jumping. Too much dark current will create a false peak in the flux measured. The dark images allow us to subtract off the dark current from the pixels. The Master Dark is subtracted from the image as seen in Figure 2.7. The application of the Master Dark helps resolve the hot pixels.

2.7 Master Flat

Another instrumental error arises because of how the telescope lens opens. The DDT opens from the center. This means that the middle of the frame has more illumination than the surrounding
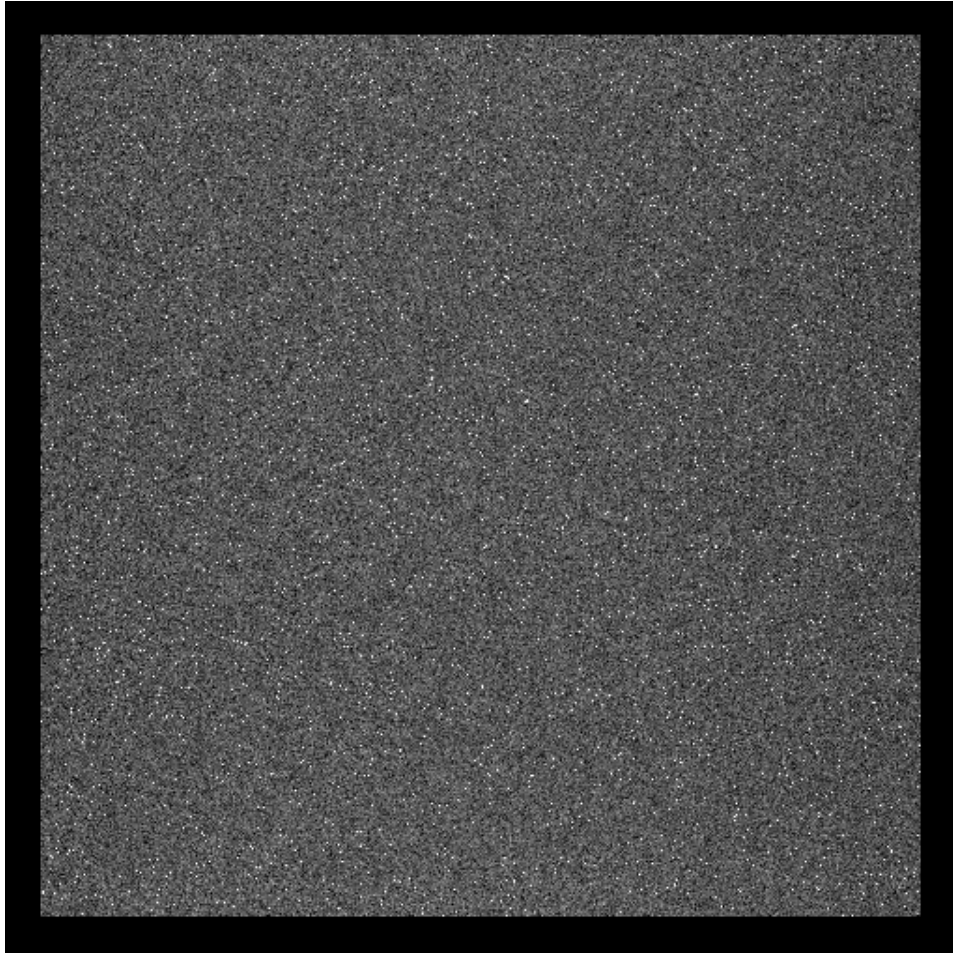
Figure 2.6 The Master Dark is a compilation of all the dark frames. It will be applied to the raw images to get rid of the dark current. The white specks seen are hot pixels.
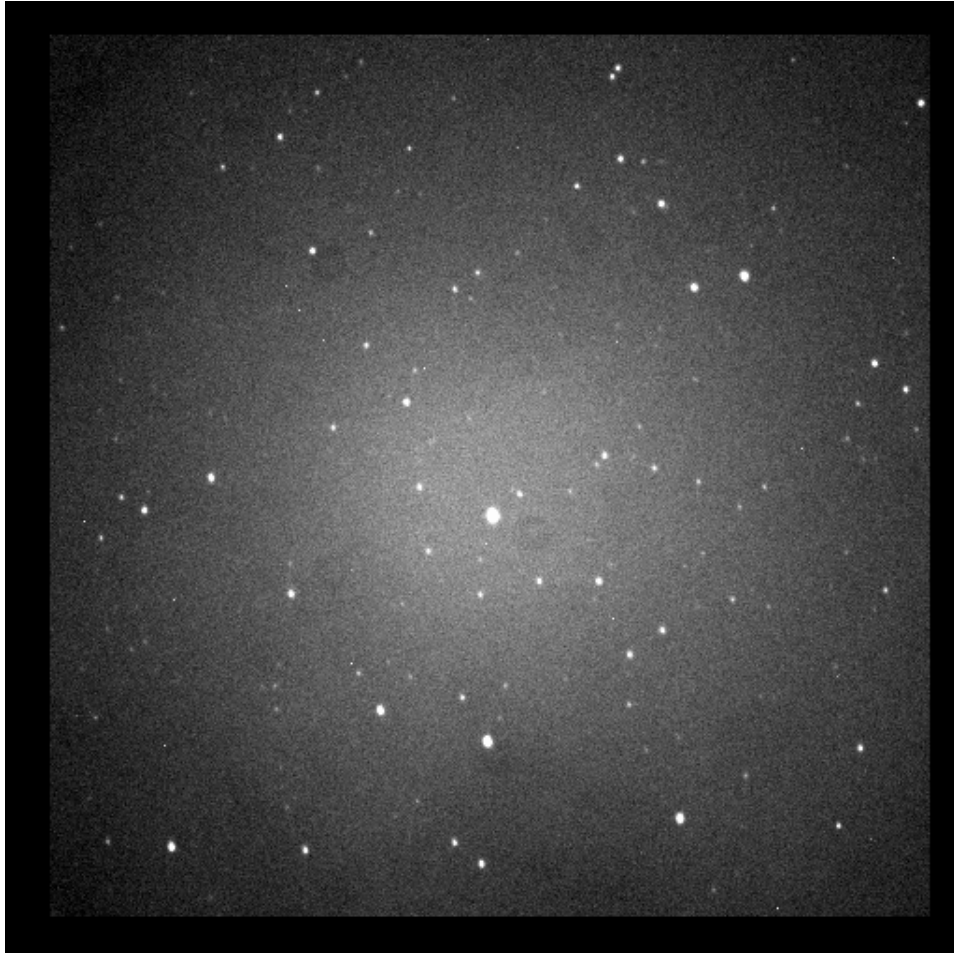
Figure 2.7 The Master Dark is subtracted from the image after the Master Zero has been subtracted out. The Master Dark resolves the hot pixels on the image.
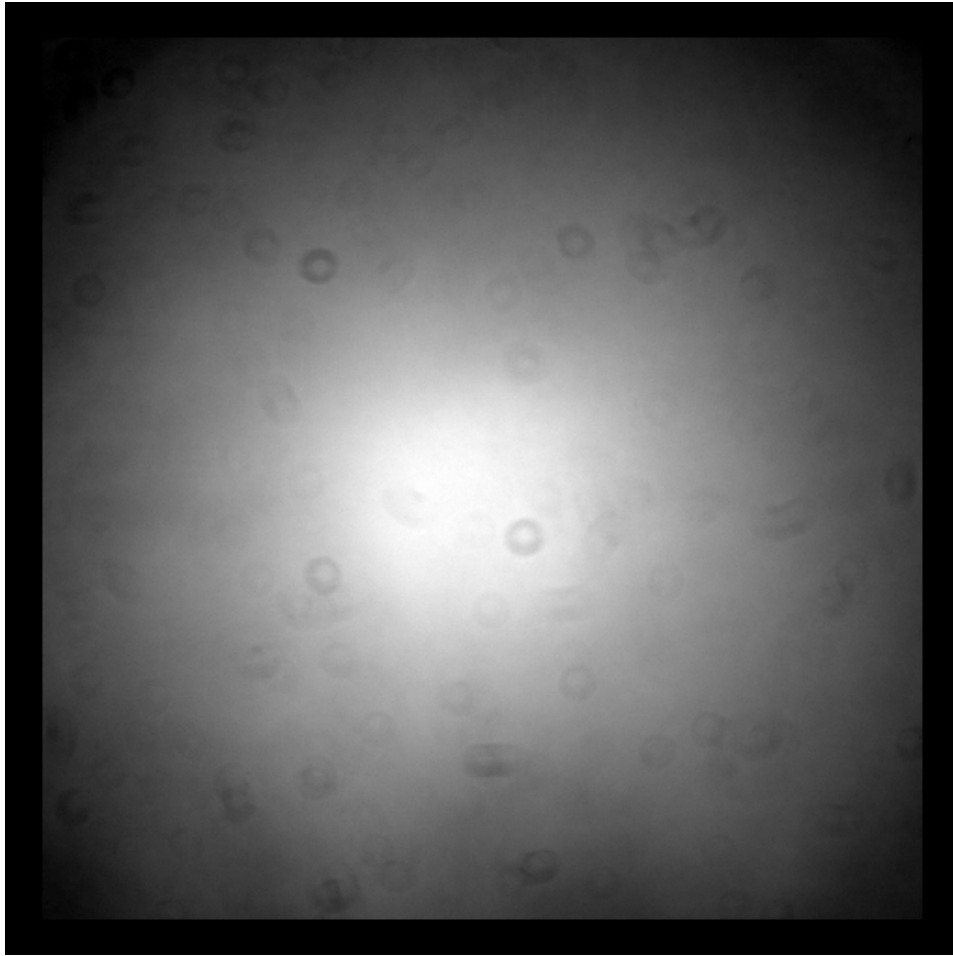
Figure 2.8 The Master Flat is taken to make the illumination uniform. The center of the image receives more light than the corners and so the illumination needs to be spread out or flattened to normalize the field of the raw image. The Master Flat also corrects for dust and other particles, which are the circles on the image above.

area. This nonuniform illumination offsets the accuracy of creating a light curve. To make the frames uniform in illumination, flat frames are taken. The purpose of flat images are to remove the error in exposure and resolve the uneven illumination of the image.

The flat images are taken with the intent to normalize the field of the image of the twilight sky. The flat images are taken without saturation to see how the illumination is that particular night. The Master Flat is a compilation of all the flat field images as seen in Figure 2.8. The Master Flat

Figure 2.9 The Master Flat is divided out of the image after the Master Zero and Master Dark are subtracted out. This makes the illumination of the image uniform. The raw image is now completely data reduced and ready for photometry.

is applied to the image to make the illumination of the image more uniform as seen in Figure 2.9.

The flat field is filter dependent.

2.8 Filter

Filters are used to collect images in different wavelengths. The DDT has several filters that can be used; the most common are Blue (B), Infrared (I), Visible (V) and Red (R). Certain filters get

better readings of the host star because they measure a deeper section of the host star's wavelength. Filters block out parts of the wavelength spectrum and this makes the signal to noise better for the target wavelengths. For example, red stars are better observed in the B filter than I filter and will give a deeper light curve in the B filter. The filters on the raw image alternate to help broaden the data as certain wavelengths won't show a one percent dip in the light curve. Each Master Flat has a subset that corresponds to a specific filter. An R filter will not be applied to an image taken in the V filter. IRAF prevents filters from being mismatched to an image of a different filter. The filters are taken into account when the Master Flat is applied to the image. This is the final step in the data reduction process.

2.9   Processed Images

The processed image is made from the application of the Master frames to the raw images of the night. The Master Zero and Master Dark are subtractions to the raw images, while the Master Flat is a division to them. A comparison of a raw image and processed image can be seen between Figure 2.10 and Figure 2.11, respectively. Once the Master frames have been applied to each image, the images are then ready to be used for study. Photometry is the measure of the flux of the image, and with the application of the Master frames, the processed images give accurate results of the measured flux.
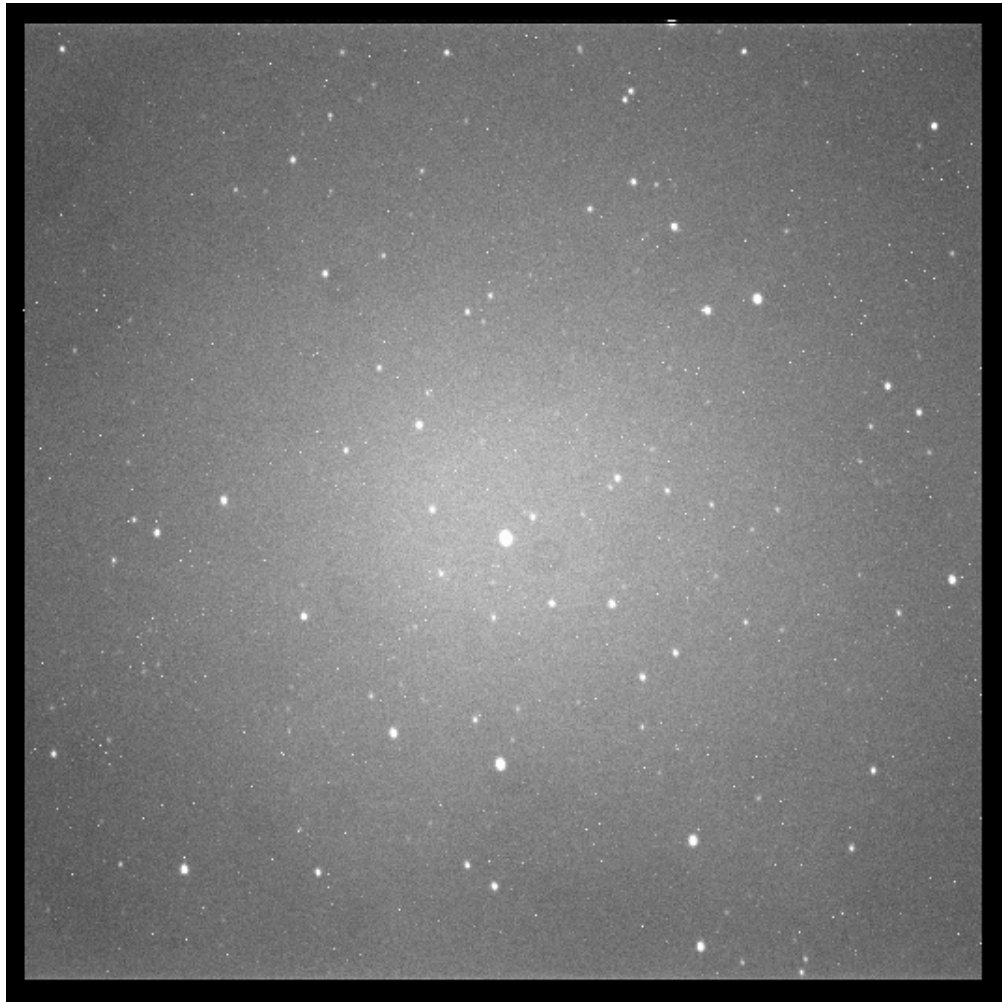
Figure 2.10 This is an image before the DR script is run on it. There's no flux along the edges of this raw image. The illumination isn't uniform and there are excessive white specks throughout the image. It would be impossible to get an accurate light curve from the image in its current state, thus missing a possible transiting planet.

Figure 2.11 This is the final product of the DR script. This is one of many images that is now ready for photometry. The image should be a replica of when the Master Flat is divided out.

Chapter 3

Data Analysis

The purpose of the DR script has been to prepare the raw images for photometry. This chapter details how the processed images have their light measured. The light curve produced from a transiting planet is just about one percent. Because the instrumental errors have been subtracted and divided out of the original images, the interesting physics can begin. Two nights of data are shown as an example of how effective the pipeline is in producing reliable processed images.

3.1   AstroImageJ

The measurement of flux, also known as photometry, yields useful data for astronomers. The results of photometry can prove the existence of a transiting planet. The light curve obtained from transiting planets tends to be a dip of about one percent in flux. This small measurement of change in flux has been the reason why the DR script is of importance since it alleviates the known instrumental errors. AstroImageJ (AIJ) (Collins 2017) is a specialized program for photometry. The processed data can be read into AIJ to find the light curve of the host star of the transiting planet.

To find the light curve of the host star, the processed data is imported to AIJ. Once uploaded,

the host star is selected first and denoted as the target star. Several other stars are also selected to be comparison stars. The comparison stars are used by AIJ as a standard to help give an accurate interpretation of how light varied throughout the night. The target star and comparison stars are plotted out on a graph of time vs. flux. Airmass and total sky count are also plotted out. The airmass deals with how light comes through the atmosphere and can affect the brightness of stars. A drop in airmass can drop the amount of light received by the telescope from the host star. Total sky count involves counts per pixel. A light curve has been made, however, a few parameters must be applied to help interpret the light curve plot.

A black line is fitted to the light curve of the target star, the red dots. The fit that the black line makes comes from the data that the DR script has processed. The black line fits the red dots to a transit. The red dots have been detrended with the airmass and total sky counts. The ingress and egress times are needed to help the black line fit the transit to the estimated times received from the KELT team. The blue dots are the same target star as the red dots. The blue dots have not been detrended with airmass and total sky counts. The blue dots show how the light fluctuated due to the sky and atmosphere. The light curve of the blue dots can be compared to that of the red dots.

The comparison stars are also detrended with the airmass and total sky count. The comparison stars should create a straight line and not dip in light. Comparison stars should be about the same brightness as the target star. Too bright of stars can negatively influence the light curves as other stars will appear fainter than they really are. Good comparison stars will help show a transit if it is really there.

After all has been done to maximize the results in AIJ, an analysis of the potential transiting planet can take place. As the DDT is a ground based telescope, the transiting planets found by KELT are usually Hot Jupiters, planets larger than Jupiter and very close to their host star. The light curve seen in Figure 3.1 shows a dip in light of about one percent. It is clear that something has crossed in front of the host star. The ingress and egress times however are a little off and so
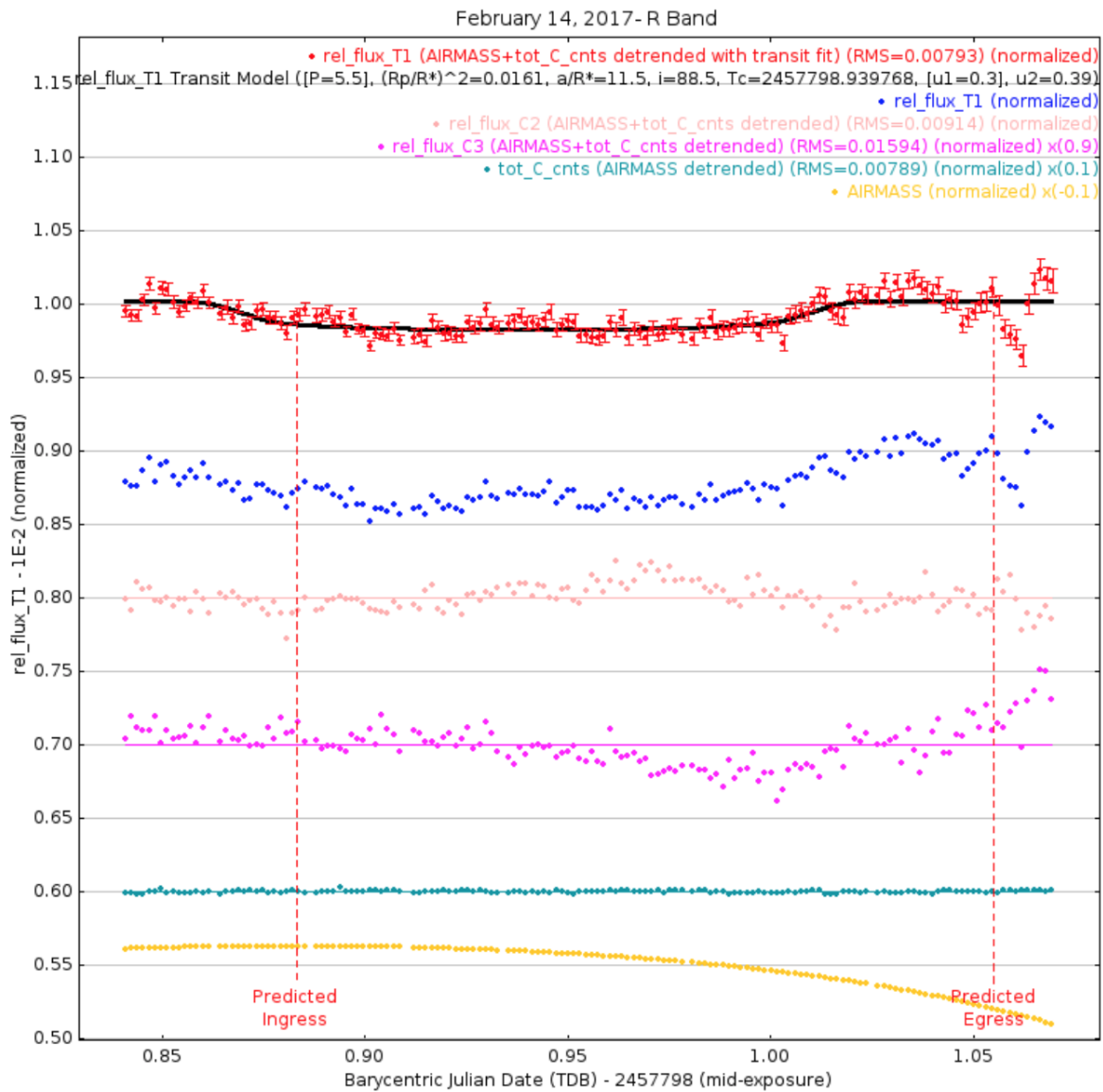
Figure 3.1 Results of AIJ from 14 February 2017. The dip in light is about one percent which fits with the estimations. However, the ingress and egress were off so the host star needs to be further observed to fix the errors in calculation.
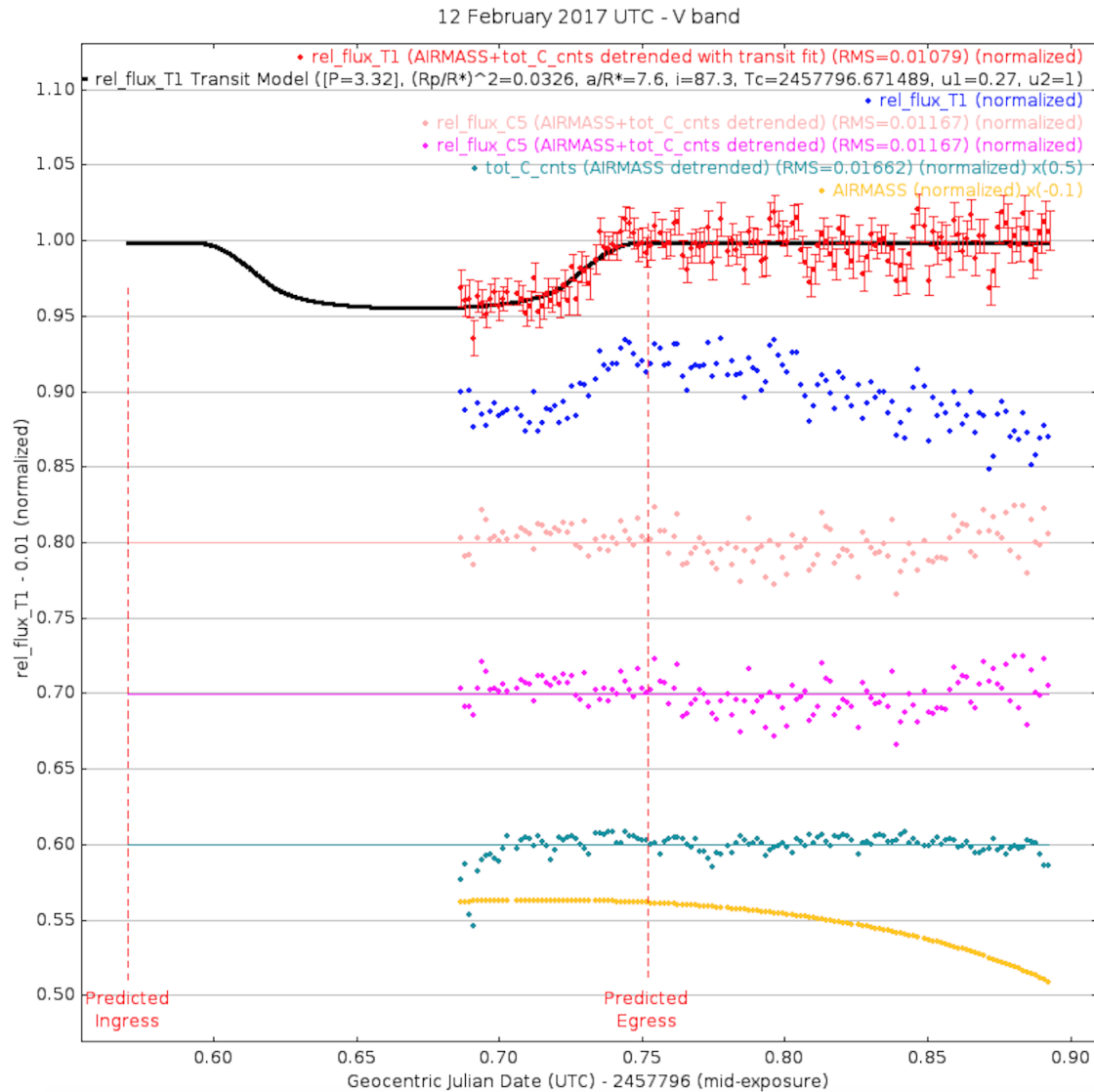
Figure 3.2 Results of AIJ for 12 February 2017. The light curve is larger than expected, about five percent. This fits more with a binary system and possibly means that this isn't a transiting planet.

this particular host star merits further study to adjust the calculations previously made. The end of the data fluctuates since the airmass is dropping off fast. All in all though, the transit fit that the black line provides is very promising. The light curve in Figure 3.2 has an egress that matches with the predicted egress, but the dip in light is much greater than one percent. This could possibly be a binary system and isn't something studied heavily by the KELT team. With the reduced turn around time provided by the efficiency of the DR script, these AIJ results can be communicated quickly to the KELT team.

The results of AIJ have been satisfying as they give credible light curves. The DR script has reduced the time in which data can be analyzed by AIJ and given back to the KELT team. The graphs from AIJ agree with the results of other members of the team. This means that the DR script is effective and reliable in removing the known errors. The results of AIJ help determine whether further investigation is needed or not. These plots, along with descriptive notes, are sent back to the KELT team for further analysis. With a decrease in turn around time, more KELT telescope time can be devoted to looking for more transiting planets.

Chapter 4

Results and Discussion

The DR script has proven to be reliable in its ability to data reduce the raw images of the night sky. The processed images produced by the DR script can be run through AIJ to verify the presence of a transiting planet. The success of the current DR script is discussed as well as improvements for the future. Advice is given on how to maintain the DR script. The light curves that come from the processed images align with the research of other KELT team members.

4.1   Results

The processed images have given reliable results when run through AIJ. The DR script correctly streamlines the raw images into processed ones. The success of this DR script is critical to the KELT team as it reduces the time in which communication happens. The continued use of this program after data has been collected means that instead of spending several hours reducing the data by hand, the raw images can be reduced quickly once the data has been collected.

4.2   Current Script

Because of limitations in IRAF, the data reduction process can still have a few errors in the future. These errors have to be watched for to avoid incorrect results. This occurs because IRAF is a black box program that originated in 1986. The packages that IRAF can access are extremely useful. However, because of the finickiness of IRAF, it often requires trial and error to figure out the explicit commands to use each package fully.

To be successful in operating IRAF it is essential to be exact with wording. Misspelling or incorrect punctuation will terminate programs in IRAF. Also, certain packages need to be included in the user's login.cl to activate them. The benefit is that IRAF does have all of the necessary tools to correctly reduce the data as seen by the success of this DR script and its preparation for photometry.

Besides the typical troubleshooting, the current script does need an update to the BPM quarterly. This is necessary since both bad pixels which are comprised of dead pixels and some hot pixels, vary. If the bad pixel mask isn't updated then the script will reduce data with the assumption that the current BPM is the desired aid in the reduction process. The BPM can easily be updated with on-line instructions.

4.3   Discussion

The current DR script sufficiently reduces KELT data. Because the DR script is successful, we can focus on the physics that is interesting: photometry. The DR script is currently being used, and the resulting data is comparable to the KELT team since it matches other teams' research done by hand as well.

However, there are a few things that could still be worked on for the current DR script. The biggest factor is the dark time integration. The Master Dark counts the electrons that have jumped

the band gap without being triggered by a photon. There should be a linear relationship between the electrons that jump and the exposure time of the lens when taking dark frames. However, this relationship isn't as linear as desired. Future work of the dark frames would help solidify the usefulness of the DR script and improve the sensitivity of the one percent dip in light we are expecting to see when using programs such as AIJ.

Appendix A

Instructions for Running dr.cl

This is the code for the data reduction script. The script is broken into several command lines with the intent to facilitate debugging as well as to be easy to use for quick corrections. The main script used is dr.cl, which calls all the other command lines in the appropriate sequence to reduce the night's data.

```
# This program updates the headers so that later the CMDS file can be
easily applied.

print("editing the headers on the object (on all images)")

#*.fit allows all images to be adjusted, this means that this will
make images that start with K or H into imagetyp
hedit ("*.fit",
"imagetyp", "object", add=yes, addonly=yes, delete=no, verify=no,
show=yes,
update=yes)

print("editing the headers on zeros")
#this *z.fit will need to be changed to z*.fit
hedit ("*z.fit",
"imagetyp", "zero", add=yes, addonly=yes, delete=no, verify=no,
show=yes,
update=yes)

print("editing the headers on darks")
hedit ("*d*.fit",
"imagetyp", "dark", add=yes, addonly=yes, delete=no, verify=no,
show=yes,
update=yes)

print("editing the headers on flats")
hedit ("flat*.fit",
"imagetyp", "flat", add=yes, addonly=yes, delete=no, verify=no,
show=yes,
update=yes)

# This updates the headers for the filters
print("editing the headers for filters")
hedit ("flat*b.fit",
"subset", "B", add=yes, addonly=yes, delete=no, verify=no, show=yes,
update=yes)

hedit ("flat*B.fit",
"subset", "B", add=yes, addonly=yes, delete=no, verify=no, show=yes,
update=yes)

hedit ("flat*r.fit",
"subset", "R", add=yes, addonly=yes, delete=no, verify=no, show=yes,
update=yes)

hedit ("flat*R.fit",
"subset", "R", add=yes, addonly=yes, delete=no, verify=no, show=yes,
update=yes)

hedit ("flat*v.fit",
```

Figure A.1 This script updates the headers of the images to be functional in IRAF.

```
#This part trims all of the images

print("Applying BadPix_Mask.pl and trimming")
print("Update BadPix_Mask.pl for current semester")

ccdproc ("*.fit",
output="", ccdtype=" ", max_cache=0, noproc=no, fixpix=yes,
overscan=no,
trim=yes, zerocor=no, darkcor=no, flatcor=no, illumcor=no,
fringecor=no,
readcor=no, scancor=no, readaxis="line", fixfile="BadPix_Mask.pl ",
biassec=" ",
trimsec="[86:1971,88:1973]", zero=" ", dark=" ", flat=" ", illum="",
fringe="", minreplace=1., scantype="shortscan", nscan=1,
interactive=no,
function="legendre", order=1, sample="*", naverage=1, niterate=1,
low_reject=3., high_reject=3., grow=0.)
```

Figure A.2 This script trims the images to get rid of vignetting and excess electronic heat on the edges.

```
#Program to create master zero

noao
imred
ccdred

print("Starting zerocombine")


zerocombine ("*z.fit",
output="Zero", combine="median", reject="avsigclip", ccdtype="zero",
process=no,
delete=no, clobber=no, scale="none", statsec="", nlow=0, nhigh=1,
nkeep=1,
mclip=yes, lsigma=3., hsigma=3., rdnoise="0.", gain="1.", snoise="0.",
pclip=-0.5, blank=0.)

ccdproc ("*.fit",
output="", ccdtype="dark", max_cache=0, noproc=no, fixpix=no,
overscan=no,
trim=no, zerocor=yes, darkcor=no, flatcor=no, illumcor=no,
fringecor=no,
readcor=no, scancor=no, readaxis="line", fixfile="", biassec=" ",
trimsec="[16:4105,35:4110]", zero="Zero.fits", dark="Dark.fits",
flat="Flat*.fits", illum="", fringe="", minreplace=1.,
scantype="shortscan",
nscan=1, interactive=no, function="legendre", order=1, sample="*",
naverage=1,
niterate=1, low_reject=3., high_reject=3., grow=0.)

print("Created Master Zero")
```

Figure A.3 This script creates the master zero.

```
#Program to create master dark

print("Starting darkcombine process")

print("If program is interrupted, then it means that the master zero
was not created. Go back to make sure there is a master zero in the
folder that is being called. You will then have to start your program
from this point on.")

darkcombine ("*d*.fit",
output="Dark", combine="median", reject="avsigclip", ccdtype="dark",
process=yes, delete=no, clobber=no, scale="none", statsec="", nlow=0,
nhigh=1, nkeep=1, mclip=yes, lsigma=3., hsigma=3., rdnoise="0.",
gain="1.",
snoise="0.", pclip=-0.5, blank=0.)

ccdproc ("*.fit",
output="", ccdtype="flat", max_cache=0, noproc=no, fixpix=no,
overscan=no,
trim=no, zerocor=yes, darkcor=yes, flatcor=no, illumcor=no,
fringecor=no,
readcor=no, scancor=no, readaxis="line", fixfile="", biassec=" ",
trimsec="[16:4105,35:4110]", zero="Zero.fits", dark="Dark.fits",
flat="Flat*.fits", illum="", fringe="", minreplace=1.,
scantype="shortscan",
nscan=1, interactive=no, function="legendre", order=1, sample="*",
naverage=1,
niterate=1, low_reject=3., high_reject=3., grow=0.)

print("Created Master Dark")
```

Figure A.4 This script creates the master dark.

```
#Program to create the master flat along with the respective filters

noao
imred
ccdred

print("Starting the flatcombine process")

print("If this process is interrupted, the most likely scenario is
that you will have to create a master flat from another night. After
that is created you will need to combine the previously made master
zero and dark to the object")

flatcombine ("flat*.fit",
output="Flat", combine="median", reject="avsigclip", ccdtype="flat",
process=yes, subsets=yes, delete=no, clobber=no, scale="mode",
statsec="",
nlow=1, nhigh=1, nkeep=1, mclip=yes, lsigma=3., hsigma=3.,
rdnoise="0.",
gain="1.", snoise="0.", pclip=-0.5, blank=1.)

print("Created Master Flat and Filters")
print("Output name will be Flat[subset].fits")
```

Figure A.5 This script creates the master flat

```
#Program to create the final images fully reduced

print("Applying master zero, dark and flat to object")

noao
imred
ccdred

ccdproc ("*.fit",
output="", ccdtype="object", max_cache=0, noproc=no, fixpix=no,
overscan=no,
trim=no, zerocor=yes, darkcor=yes, flatcor=yes, illumcor=no,
fringecor=no,
readcor=no, scancor=no, readaxis="line", fixfile="", biassec=" ",
trimsec="[16:4105,35:4110]", zero="Zero.fits", dark="Dark.fits",
flat="Flat*.fits", illum="", fringe="", minreplace=1.,
scantype="shortscan",
nscan=1, interactive=no, function="legendre", order=1, sample="*",
naverage=1,
niterate=1, low_reject=3., high_reject=3., grow=0.)

print("DONE")
```

Figure A.6 This script applies all of the master images. The master zero and dark are subtracted out while the master flat is divided out.

```
#This script contains several path lengths for data reduction. When
there is an error in the program itself, come here to find the
appropriate task and start from there to solve the problem.

#Update the headers, uses the hedit command.
cl < /data/transiting.planets/pipeline/header.cl
#cl < /data/andyroo/header.cl

#Trims all of the images.
cl < /data/transiting.planets/pipeline/trim.cl
#cl < /data/andyroo/trim.cl

#Makes the master zero
cl < /data/transiting.planets/pipeline/masterzero.cl
#cl < /data/andyroo/masterzero.cl

#Makes the master dark
cl < /data/transiting.planets/pipeline/masterdark.cl
#cl < /data/andyroo/masterdark.cl

#Makes the master flat
cl < /data/transiting.planets/pipeline/masterflat.cl
#cl < /data/andyroo/masterflat.cl

#Makes the master image and is now fully reduced.
cl < /data/transiting.planets/pipeline/object.cl
#cl < /data/andyroo/object.cl
```

Figure A.7 This script calls on all of the other scripts to run automatically in order.

Bibliography

Barnes, J.: A Beginner's Guide to Using IRAF: 1993 August

Tody, D. 1986, "The IRAF Data Reduction and Analysis System" in Proc. SPIE Instrumentation in Astronomy VI, ed. D.L. Crawford, 627, 733

Oberst, T., et al.: KELT-16b: A Highly Irradiated, Ultra-short Period Hot Jupiter Nearing Tidal Disruption: The Astronomical Journal: 2017 March

Collins, K., et al.: AstroImageJ: Image Processing and Photometric Extraction for Ultra-Precise Light Curves: The Astronomical Journal: 2017 January

Ranquist, E.: A Compilation and Description of Scripts Written for the Optimization of Photometric Procedures: BYU: 2013 August

https://www.eso.org/sci/facilities/lasilla/instruments/efosc/inst/BADPIXMASK.html#make

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