Reduction and Analysis of KELT Data

to Confirm Transiting Planets

Benjamin Fischer

A senior thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Bachelor of Science

Denise Stephens, Advisor

Department of Physics and Astronomy

Brigham Young University

December 2015

ABSTRACT

Reduction and Analysis of KELT Data
to Confirm Transiting Planets

Benjamin Fischer
Department of Physics and Astronomy, BYU
Bachelor of Science

The Kilodegree Extremely Little Telescope (KELT) program is exactly what the name suggests a small telescope that observes a large field of view. Operating since 2005 KELT has been gathering data on thousands of stars with the purpose of discovering transiting planets. KELT generally observes stars with magnitudes of approximately 10 and looks for variations in flux. The KELT team catalogs all candidates for transiting stars. Since there are many possible causes for drop in flux it is necessary to make follow-up observations on exoplanet candidates. Using information from the KELT catalog we decided on several possible target stars. Observations of the stars were done to gain more data to analyze. Using the newly gathered data we created light curves for each star. We also analyze this data to determine the cause of the drop in flux. We explain how to do this process in a way to allow others to continue this work.

Keywords: [KELT, exoplanet, light curve, transiting planet]

ACKNOWLEDGMENTS

Contents

Chapter 1

Introduction

1.1 Exo-Planets

It is an integral part of the human nature to explore. The idea of finding planets outside our own solar system is an intriguing part of discovering how our universe functions. With each exoplanet discovered we increase our understanding of solar system formation and its evolution over time. As modern technology gets better our ability to detect more of these exoplanets does too. With the idea of gaining a better understanding of solar system formation and the possibility of finding another planet in the habitable zone it is no wonder why there has been such a huge surge in popularity of finding exoplanets. The amounts of data coming in on exoplanets has never been as great as it is now. Luckily with better data reduction packages more and more people are able to participate in the finding of exoplanets.

The first planet outside of the solar system wasn't discovered and confirmed until 1992. For a very long time since 1992 the discovery of planets has been slow until the past few years. It was only recently in 2014 that exoplanet discovery truly exploded. The amounts of data coming in on exoplanets has never been as great as it is now. Luckily with better data reduction packages more

and more people are able to participate in the finding of exoplanets.

1.2   Description of Transiting Exoplanets

It is clear that the vast majority of these newly discovered planets are transiting planets as shown

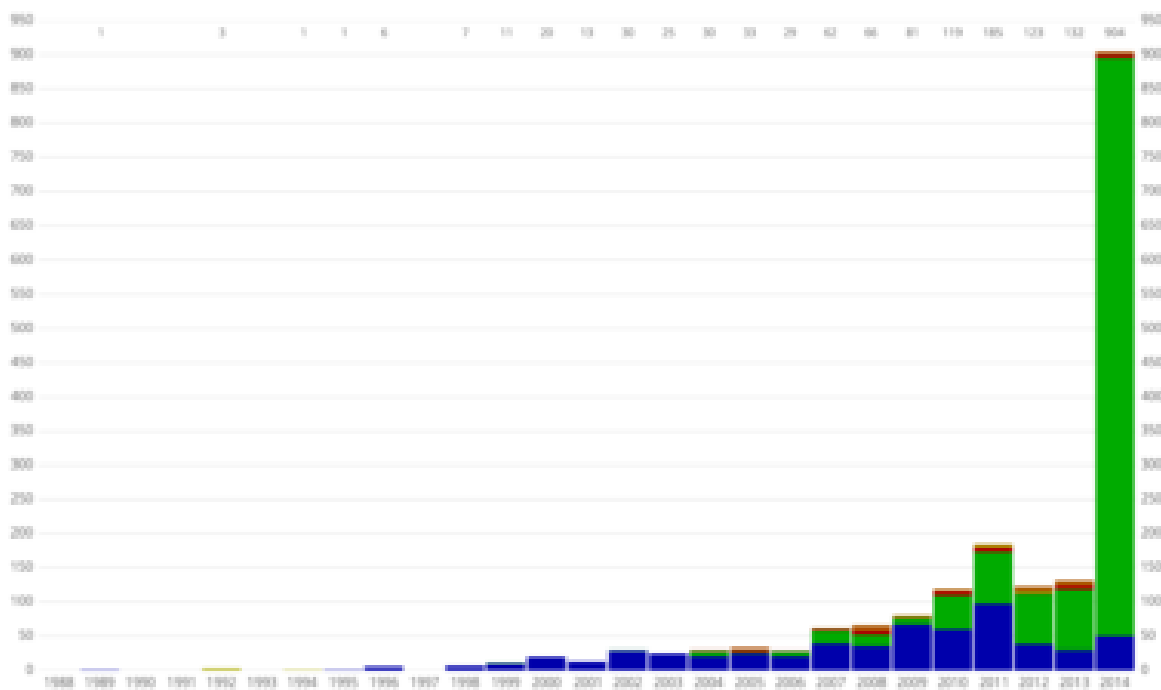in Figure 1.1. While using the method of transition is not the only method it is clearly the most

Figure 1.1 Number of exoplanets discovered and method used since 1989. As a side note the planet discovered in 1988 was never confirmed until 2002.Exoplanet data is from the Open Exoplanet Catalogue,[1] version 298ee46 âĘŚ Open Exoplanet Catalogue (2015-02-04)and the Image is from $https://en.wikipedia.org/wiki/Discoveries_of_exoplanets$

successful and fastest method available at this time. It is a method that currently can be taught and

utilized more readily.

We observe transiting planets when part of the light from a star is prevented from reaching us

here on Earth due to a planet blocking some of that light. With modern CCDs and telescopes we

can detect this small change in light. With many observations in sequence it is possible to create a

light curve which shows the drop in light each time the planet passes in front of the star. The basic idea of this light curve is shown in Figure 1.2
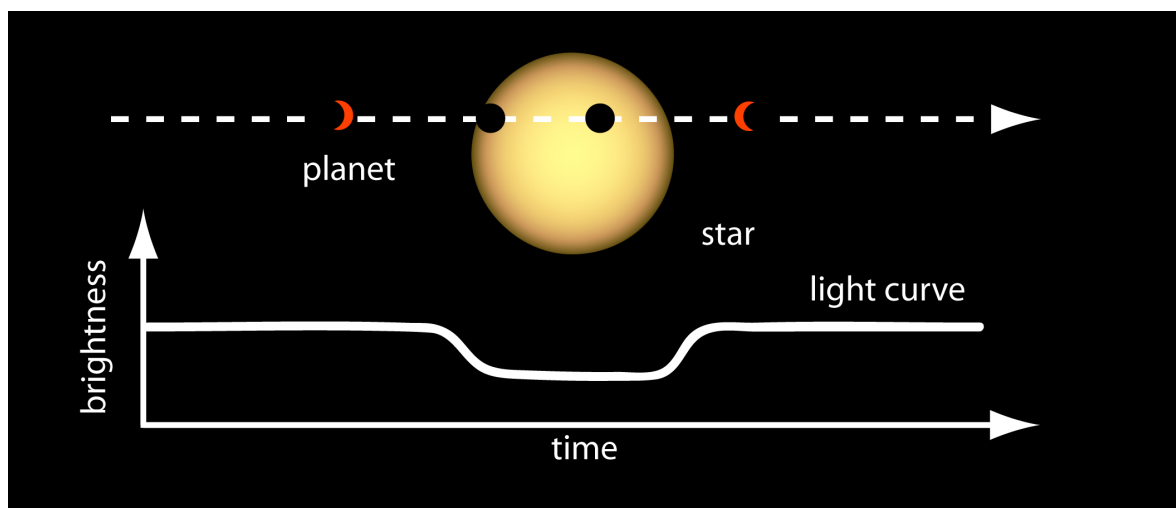

Figure 1.2 The top demonstrates what is occurring near the star. The bottom shows brightness over a time period as detected by our CCDs. This image is from $http : //www.nasa.gov/mission_pages/kepler/multimedia/images/transit - light - curve.html$

Finding transiting planets becomes more important when we realize that they can have an advantage over other methods when it comes to the understanding of exoplanets. With transiting planets we can determine properties such as internal structure of planets, atmospheric composition, and even the presence of rings or moons. (Pepper et al. 2007) Generally speaking the transiting planet method can also detect planets fainter than the radial velocity method which requires detecting the tell-tell movements of a star due to one or more orbiting planets. As you might guess this can get pretty complicated when multiple planets are in the system. Using the transition method also allows you to observe a large field although this is not always the case.

As great as the transiting planet method sounds it does have its disadvantages. We will discuss several disadvantages that we came across throughout the rest of this paper.

1.3 Description of KELT

The Kilodegree Extremely Little Telescope (KELT) program began operation in 2004 when it was installed at Winer Observatory in Sonoita, Arizona. It was designed to be able to take images of a large sky field. It essentially is a camera lens and a sensitive CCD attached to a robotic arm. Everything is automated. Generally the telescope takes exposures of 150 seconds. Each image taken gathers information on tens of thousands of stars each night so long as the weather permits. (Pepper et al. 2007).

Because KELT scans scans such a large field there are some limitations. The field KELT scans is a 26x26 degree field. Initially stars being cataloged were limited to a magnitude 8<V<10, but currently do not have an upper limit. Stars with magnitude 11<V<14 are regularly observed by Winer Observatory. The camera also cannot detect small drops in light which means the focus of KELT is the hot Jupiter size planets. This data is automatically saved to a hard drive.

This data is reduced with DAOPHOT and ISIS. DAOPHOT is used initially to compile the images and to get an initial magnitude of the stars using PSF photometry. ISIS is then used and a PSF is created for each star and light curves are created. The actual process is a little more complicated. If you'd like to understand more on how the KELT program is run please refer to (Pepper et al. 2007) and www.astronomy.ohio-state.edu/keltnorth/Method.html.

1.4 Thesis Objective

In this thesis we analyze the data we have gathered at BYU from targets picked from the KELT catalog. Essentially we will be doing follow up work on light curves discovered by the KELT team. Many different objects such as variable stars can cause us to measure periodic drops in light. The KELT does not differentiate between the different objects which cause periodic light curves. Figure 1.3 from (Pepper et al. 2007) shows different types of light curves. Our job is to look at

transiting planet candidates and decide which curves are consistent that of transiting planets. With our own data from different targets we will create light curves which will be returned to the KELT team along with data files from AstroImageJ. Ultimately we do not have the final say on whether or not the star has a transiting planet, but our data will help the KELT team make this decision. Chapter 2 will cover methodology of our data gathering and the reduction of the data. Chapter 2 will also cover any issues or problems that we came across during the process. Chapter 3 will focus on the results of different targets. We conclude in Chapter 4 and also discuss further work that needs to be done.
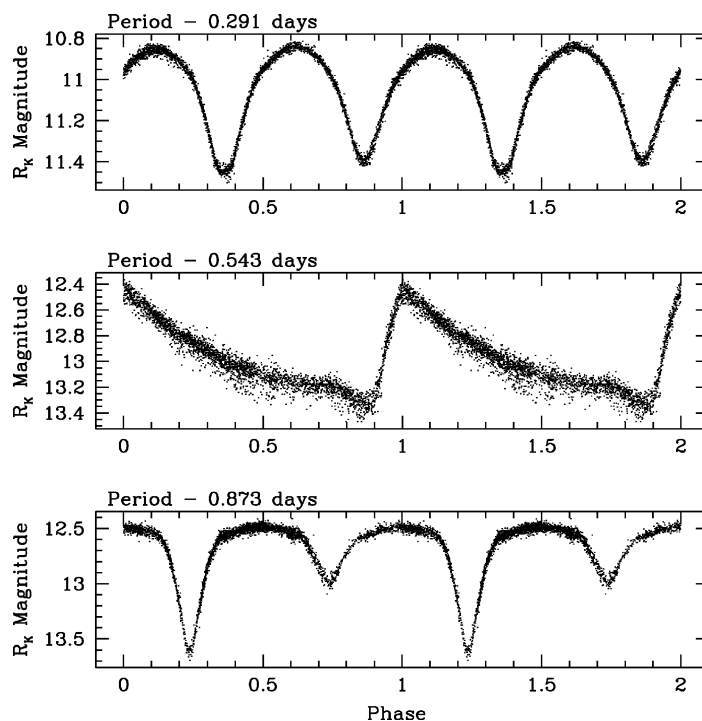

Figure 1.3 This figure shows light curves from three different variable stars that were Discovered by KELT. This shows that just because a star shows a periodic light curve does not mean it is because of a transiting planet. (Pepper et al. 2007)

Chapter 2

Observation Techniques and Data Reduction

2.1 Observational Methods

The actual observations were carried out on the .4 M David Derrick Telescope (DDT) of the Orson Pratt observatory at BYU. Flats were generally taken an hour prior to sunset. This gives enough time to be prepared to start taking observations after sunset. Whenever possible flats were also taken in the morning. The CCD in use by the DDT has very low dark current and so dark frames are rarely taken. They are taken only occasionally to confirm that it hasn't changed. The drop in magnitude of the targets vary from a few mmag up to approximately 30 mmag. The dark current was determined to be negligible and did not effect our observations. The CCD is cooled thermoelectrically to -20 degrees Celsius in summer, but can be cooled to -35 degrees Celsius in autumn and winter. Most of our observations were done in cooler weather.

The observations on each star were slightly different. The filter used on each target varied and was determined by the KELT team. Some targets had more then one filter. A new frame was taken

Table 2.1 This is an example of initial target data from the KELT team. This data shows information in star KC11C006639 and its possible transiting planet. The transiting times, duration, and period are all estimates from the KELT team based on their observations. When looking at targets from the KELT catalog we use the information below. Highest Priority is 0.

Name	V Mag	Star-Mid-End	Duration
KC11C006639	9.89	18:02-19:42-21:22	3:20

BJD (Start-Mid-End)	Elev. at Start-Mid-End	RA, Dec (J2000)	Period (Days)
7319.501-7319.571-7319.641	79°-74°-55°	19:16:20.95, +31:58:59.4	3.11

Depth (mmag)	Priority
6.1	6

at least every two minutes. Integration time varied from 20 seconds up until 120 seconds. If more than one filter was required we simply took each frame in succession. We generally stayed on the target 90 minutes after the transition or until we reached an airmass greater than 1.60. This allowed us to still see transits when the did not occur at the predicted times. All of the predicted transit times we also provided by the KELT team.

2.2 KELT Targets Used

Over 20 targets were selected from the KELT catalog and observed by BYU during our research period. Of these, we focus on eight targets in this paper. You can see the necessary information we used to select these targets in Table 2.1. These targets were observed in September and early October over the course of 9 nights. The observing and data on each target was a little different so we will be describing the observations on each target.

The first target,KC11C043952, was observed September 12, 2015. There were 356 images

taken of this object or 178 in R band and 178 in the B band. This target had good seeing and was observed from 4:40 UT to 9:30 UT. Integration time for the B and R Band was 30 and 20 seconds respectively. KC11C043952 was observed again September 21 over the course of 6 hours using 30 second integration. 500 images were taken all in the B band.KC11C043952 had 420 images taken September 24, 2015. All of these images were 30 second integration periods. A few of these points had issues as well due to clouds moving in during the observation. This didn't have a great effect on the results.

On September 22, 2015 two targets were observed. 121 KC03C05896 images were taken in the V Band. These images were integrated for 90 seconds. 188 images of 30 second integration were taken of KC11C034163 in both the I band and the B band. There were periods of hazy sky so some of the data points on KC11C034163 were omitted.

100 images were taken of KC10C26043 on September 23, 2015. This one had a few issues since the telescope operator bumped the CCD and the camera shut off. This caused us to miss a portion of important recording time. This will be understood better in Chapter 3 where we discuss the results.

KC10C05482 and KC04C032536 both had data taken on September 27th,2015, but data on KC10C05482 had already been taken and returned to the KELT team by another observer doing a similar project as us. Therefore, we will not discuss results or observations of KC10C05482. KC04C032536, however, will have is results shown in Chapter 3. There were 80 images taken of KC04C032536 in the R band. The integration time for KC04C032536 was 120 seconds per image.

On October 7, 2015 we took 35 images of KS14C032889 in the R band and V band. These were integrated as 90 seconds each. There were only 35 images taken of this star and there were some cirrus clouds during observations, but the results returned from the data reduction of this star shows that the results we get are still reliable.

KW20C05168 had 374 images take in the R band on October 11, 2015. Each image was

integrated for 60 seconds. There were several issues during the observation. The computer had issues during a required pier flip. The gears from the automatic tracking system were getting slightly caught during image integration. This effect can be seen in Figure 2.2. During the initial observations there was a thin cloud covering. About a fourth of the way through the observation the dome had to be shut due to fireworks at the nearby football stadium on the BYU campus. Observations also stopped midway through the predicted transit due to a high air mass.

Finally we observed KC11C006639 on October 24, 2015. 101 observations in each the V and R bands. Integration time was 30 seconds for both bands. This night was a good night and we did not run into any major issues.

2.3   IRAF Reduction Methods

IRAF was used to do the reduction of the raw data. This process was fairly and straightforward and simple. First the images including, dark, flats, and zeros had to be trimmed using ccdproc. The images required trimming because of the issues with the edge of the star field on the CCD. This eliminated any issues that could arise when the images were processed. Next we used IRAF to reduce the images with the darks, flats, and zeros. It is important to remember, however, that there was negligible amount of back ground current and so the darks where not actually needed in the reduction process. We subtracted the zeros from the flats and also from the images of the star field itself. The Flats were then normalized divided subtracted from the images of the star field.

2.4   Astroimage J

Astroimage J has been a wonderful tool. It has allowed us to process images must faster than allowed in IRAF. With Astroimage J we can do multi-aperture photometry on a series of images. It has several options that we can adjust in order to get a good fit for the light curve of the target

star.

The process is also generally straightforward. We imported all of the images for a star in one band at a time. We can select the target star and as many comparison stars as we like. The only issue is that if we start choosing more then 10 comparison stars Astroimage J runs the chance of crashing. Figure 2.1 is an example of this process of selecting stars. Once the stars were selected we were able to run the program which will automatically analyze the record the relative flux of the same selected stars in each image. The annulus will generally adjust automatically with each frame and so on a good day the program will run straight through without any problems.
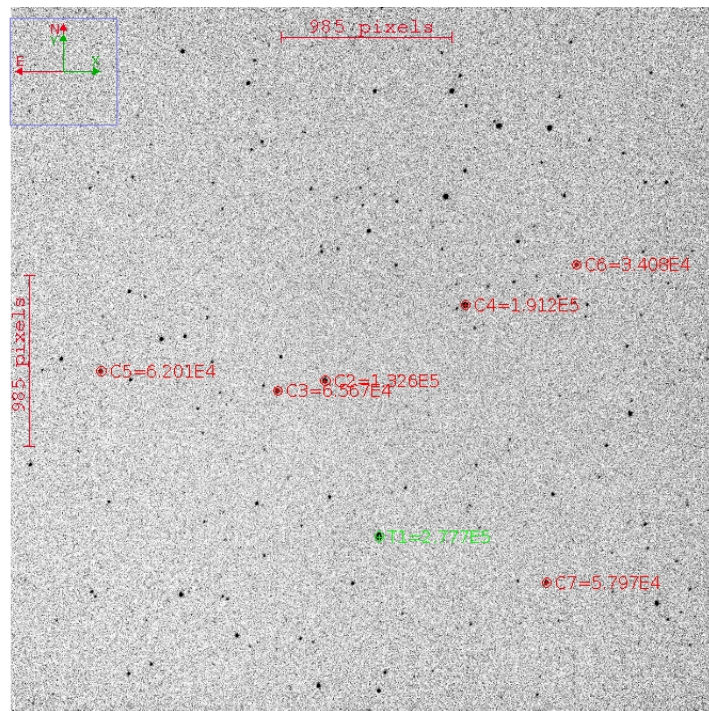
Figure 2.1 This field from October 24, 2015 shows the target,KC11C006639, in Green and the comparison stars in red. This is how the field is selected.

There are issues to take into account with this first step in Astroimage J. The annulus generally follows the same stars from frame to frame. This isn't always the case. Sometimes there are mechanical issues with the telescope gears as seen in Figure 2.2. When this is the case you must one by one delete effected images from the stack. At other times there is a pier flip. This is not as
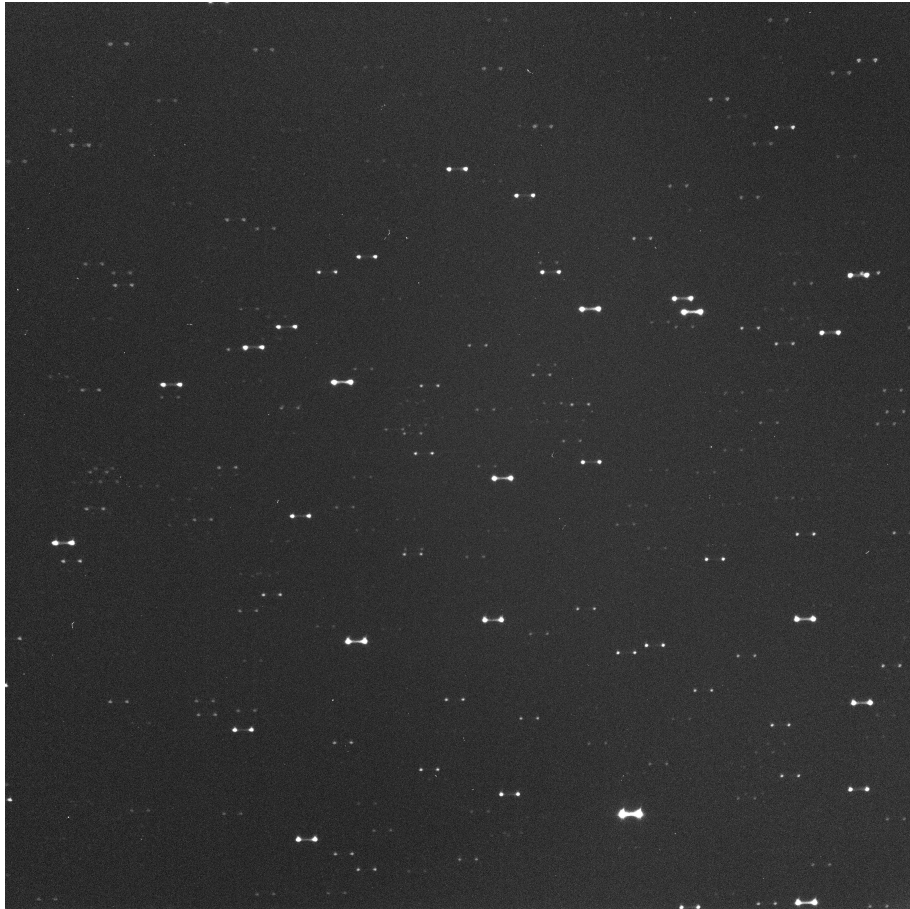
Figure 2.2 During the observation of KW20C05168 the gears were getting caught causing what I like to call the barbell effect.

much of a problem. We simply need to stop the Astroimage J process from running when we get to the flip. We can then clear the apertures and then reselct the same stars in the same order. This is necessary since the stars will all be in completely different places and Astroimage J is unable to track the stars if they have a major position change from one frame to the next. Once the apertures have been placed again we can resume the process. Since the stars have greatly changed position on the CCD we also have to trend all the data to the pier flip as pixels are known to have different sensitivities.

Once the images have been processed we make adjustments to the plot configurations. We

Figure 2.3 This is an example of what the fit panel would look like. For our purposes we
only adjust the values of J-K and Period and the rest is calculated automatically.

need to Astoimage J what the predicted period is. We also tell it what J-K value is. The J and K
magnitude values come from the SIMBAD database. You can see what the fit panel is in Figure
2.3. With this information combined with the information gained from each frame Astroimage J
will automatically calculate temperature, radius, mass, and density of the target star. All of this
information is necessary for the best fit possible.

An important part of the information returned by Astroimage J is the ratio of the radius of the
planetary radius to the radius of its host star. We can use that ratio in the equation:

$$mmag = -2.5 * Log(1 - (R_*/R_p)^2) * 1000 \tag{2.1}$$

where *mmag* is the calculated drop in light, R_* is the stellar radius, and R_p is the planetary radius. We use this equation to see if the drop in light we get in Astroimage J compares to what was predicted by the KELT team. Because there is always some error in observation often a curve is returned by Astroimage J, but the drop in light is too small to be a transiting planet. For this reason it can be important to use Equation 2.1 to confirm the results.

Chapter 3

Results

Now that we have discussed the observations and data reduction process we will look at the light curves and results of the stars.

3.1   KC11C043952

This star was reduced by another undergraduate student here at BYU. He requested a second. I was able to get the data reduced in IRAF, but unable to produce a useful curve using either the B or R bands for data gathered on the 21st. The data is maintained on an external hard drive. Unfortunately, we have been unable to get data prepared to return to the KELT team.

3.2   KC03C05896 and KC11C034163

This data has also been reduced in IRAF only. Unfortunately we have not been able to produce significant results in AstroImage J.
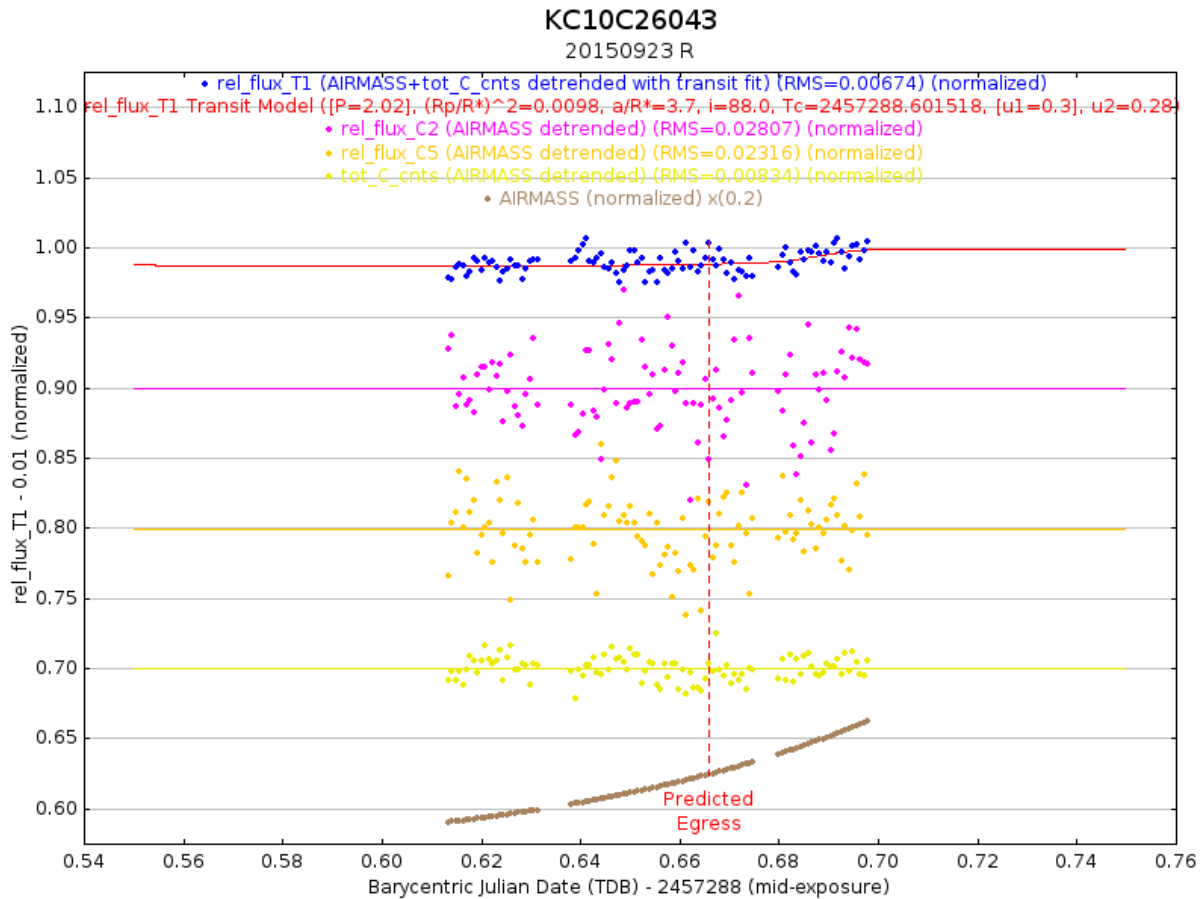
3.3   KC10C26043

Figure 3.1 This shows the target star in blue with a fitted curve shown as a red line. Brown is showing how the air mass changed over time. the other data points show some of the comparison stars.

As you can see from figure 3.1 we were unable to gather data early on during the ingress. This was due to the camera having been shut down. This doesn't necessarily mean we can't get a good curve and detect a transit. The most important part is that we capture either the ingress or egress so that we can determine if the light dropped or increased. In our reduction some of the comparison had a low signal to noise ratio due to the low magnitude. New comparison stars were selected and Astroimage J was run again. This still did not change the results significantly as can be seen by
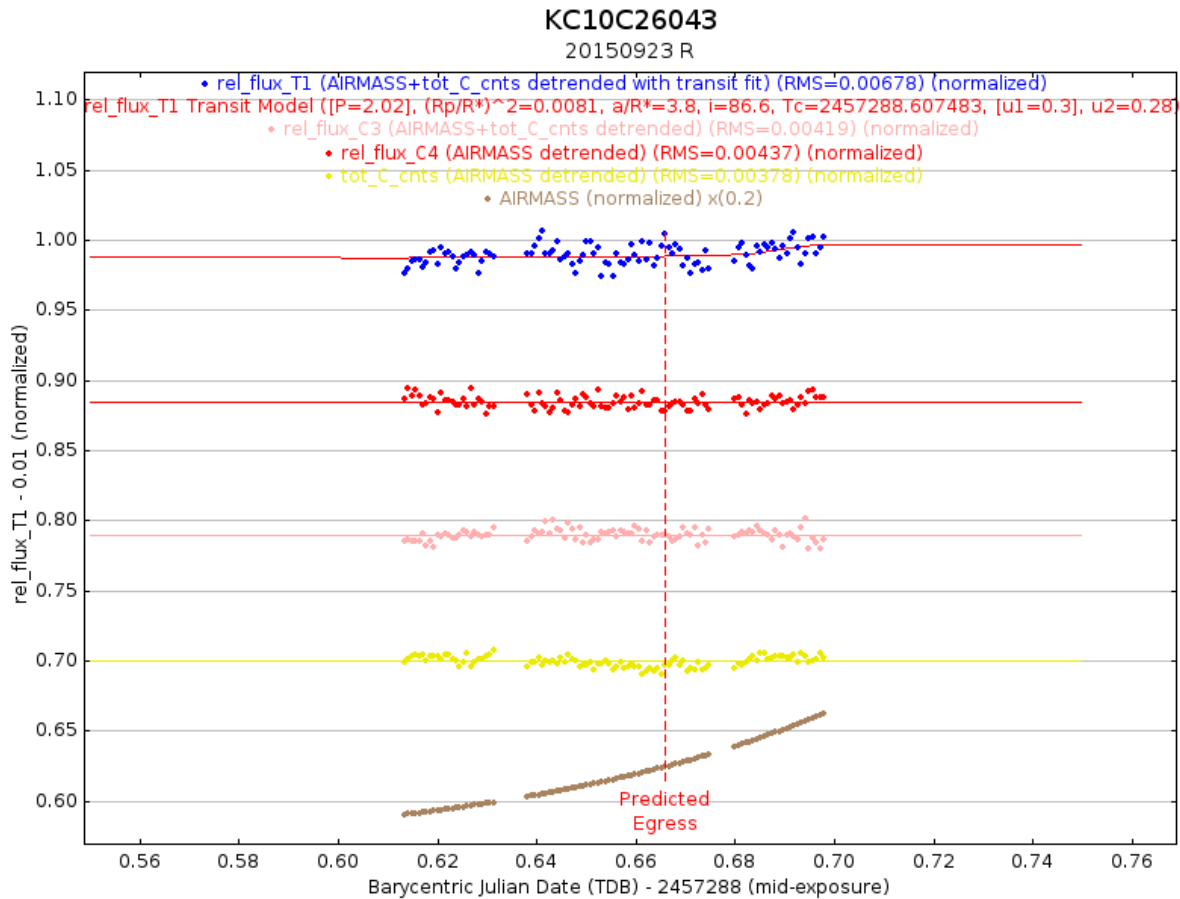
Figure 3.2 The new stars selected are not nearly as noisy as the original comparison stars. This can cause a big change, but in our case the change was negligible.

comparison of the blue data points in Figures 3.1 and 3.2 . When we use equation 2.1 we see a significant drop in light. With the change of comparison stars, shown in Figures 3.3 and 3.4, we get a smaller, but still similar drop in light detected. The transit is occurring later then predicted. These predictions are just a best guess at when the planet will transit. This is why it is important, whenever possible, to begin observing 90 minutes prior to the predicted transit time and continue 90 minutes after the predicted egress. This is possibly a transiting planet and will require more transits to be observed.
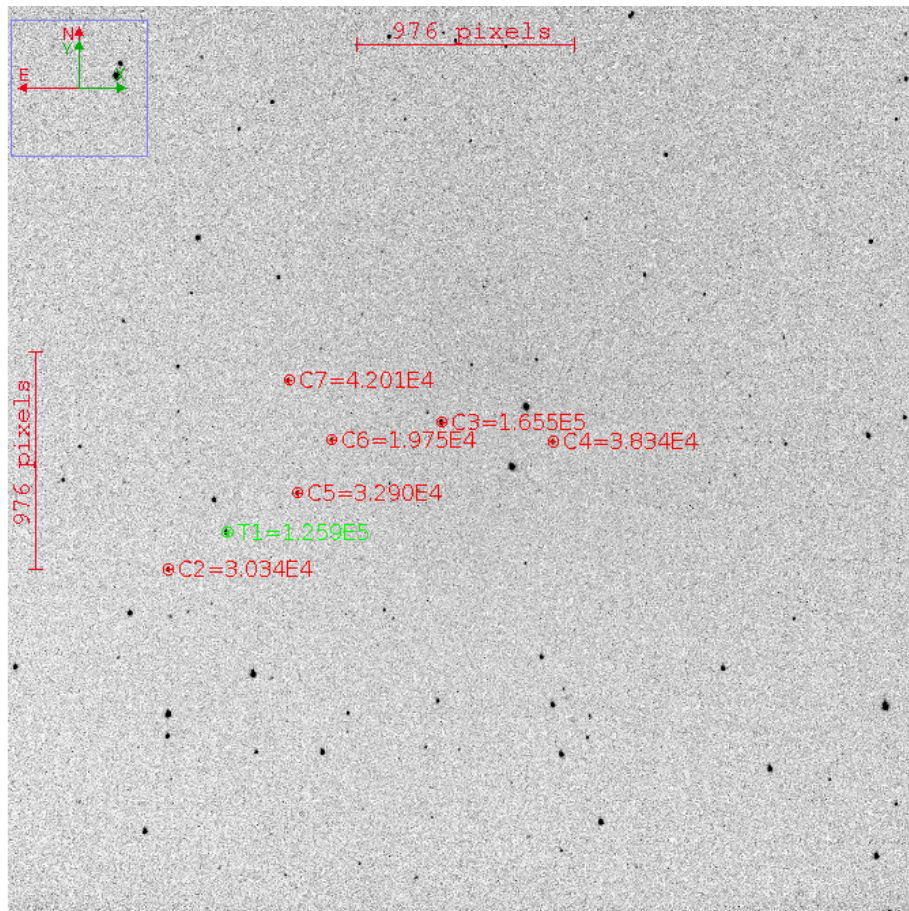
Figure 3.3 These stars while close to the target were noisy. Using comparison stars close to the target can possibly reveal why false observations of transiting planets were seen, but it can be a problem if the are not bright enough.

3.4 KC04C032536

Sometimes KELT can return a false transiting planet. This means that nothing is really happening with the star at all. What is sometimes happening is that nearby stars may be variables that caused a the false identification of a transiting planet. It becomes necessary for to select comparison stars nearby the target star and to run the images through Astroimage J again. This is what we have done with KC04C032536 as seen in Figure 3.3. An issue with using this this is that comparison star may be too dim for us to get a good signal to noise ratio. After trying this method we still did
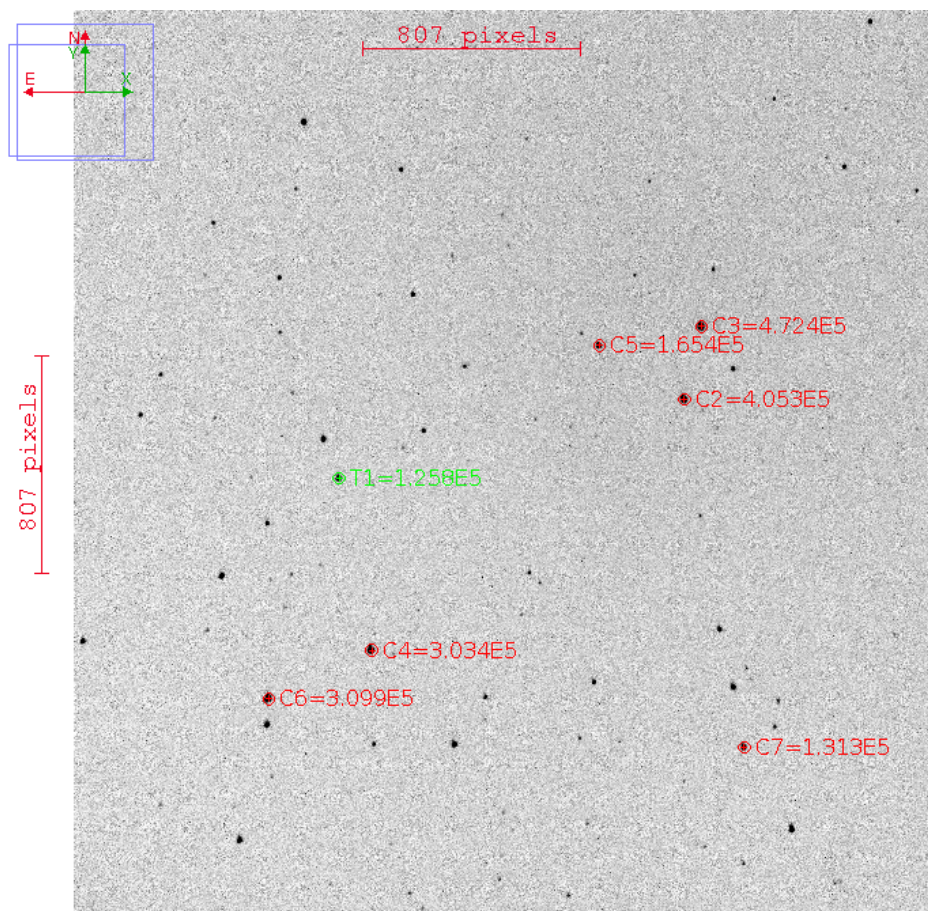
Figure 3.4 These show better what brighter stars should look like. As seen in Figures 3.1 and 3.2 these can change our results.

not get detect a transit. after applying the calculated R_p/R_* ratio to equation 2.1 we did not detect a significant drop in light. Our predicted drop in light was 3.0 mmag. We actually calculated a drop of 1.6 mmag. These results in transit depth are small and could be caused by noise during observing. You can see the results in Figure 3.6.

3.5   KS14C032889

Before you get too excited about how awesome these results are and look at Figure 3.7 please note that we accidentally left the title of this star as KC10C026043 when in reality it is really target star
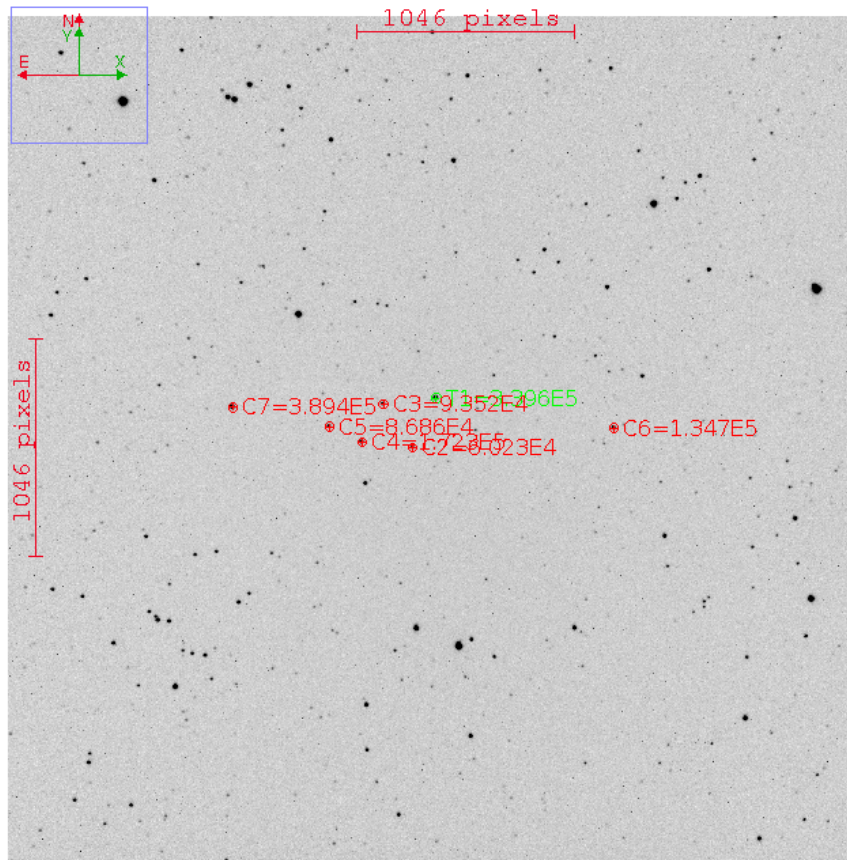
Figure 3.5 The comparison stars were all selected near the target star.

KS14C032889 from October 7, 2015. This star displayed the most exciting results. Very similar results were achieved by BYU professor Dr. Mike Joner before we actually achieved these results so I would like to make sure he receives credit for his hard work.

As can be seen in Figure 3.7 there is a significant drop in light that we detected. This star needs to be followed up on in order to find a more accurate period. We were lucky to catch the egress. It does not line up perfectly with the prediction, but further observations can reveal why this is the case. In this planet definitely hosts at least one planet.
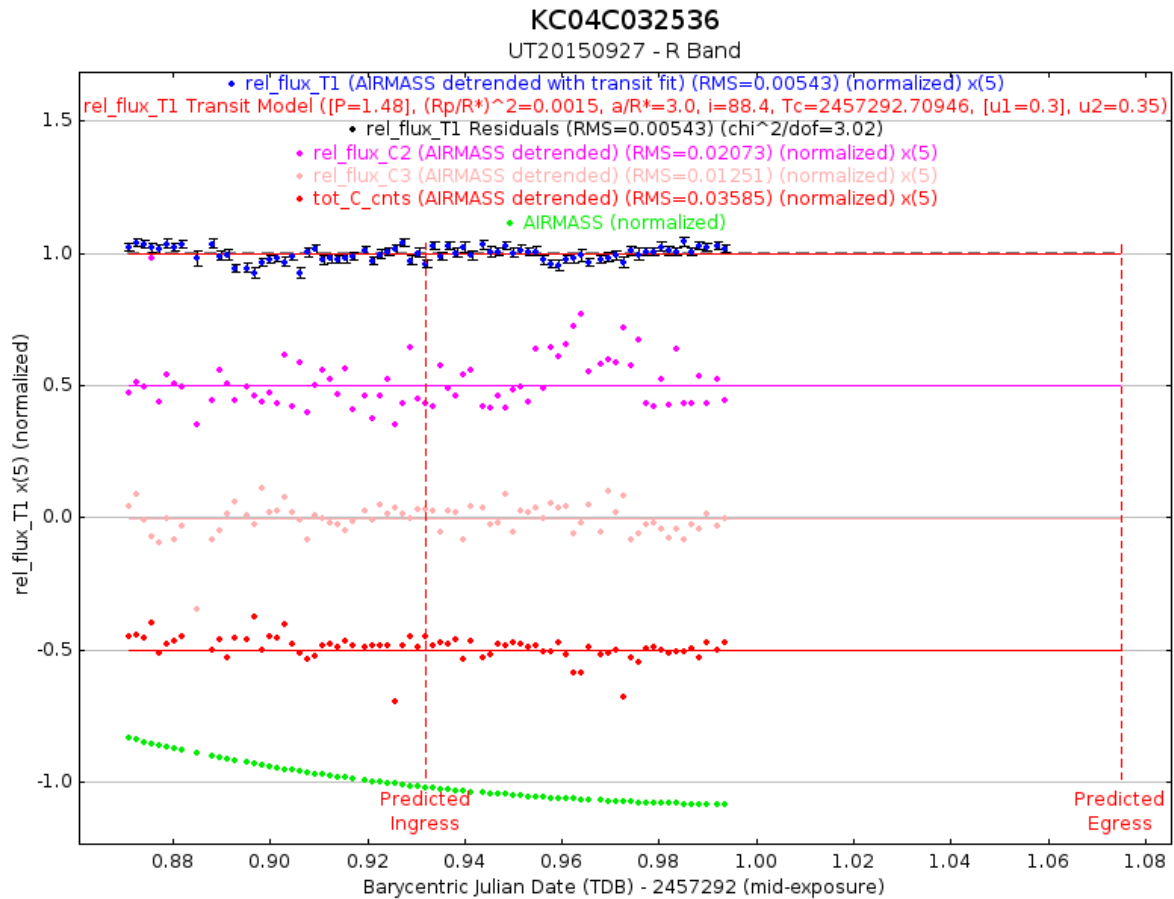
Figure 3.6 There was not a significant drop in light as is seen by the blue data points. This data is displayed with error bars.

3.6 KW20C05168

KW20C05168 was a difficult star to deal with due to problems with clouds, the pier flips, and gears catching on the tracking system. This made it difficult to reduce the data. A large portion of data points had to be removed due to the barbell effect we referred to in the caption of Figure 2.2. Taking all of this into account we were unable to produce a meaningful light curve with the data. We will leave this part up to another researcher.
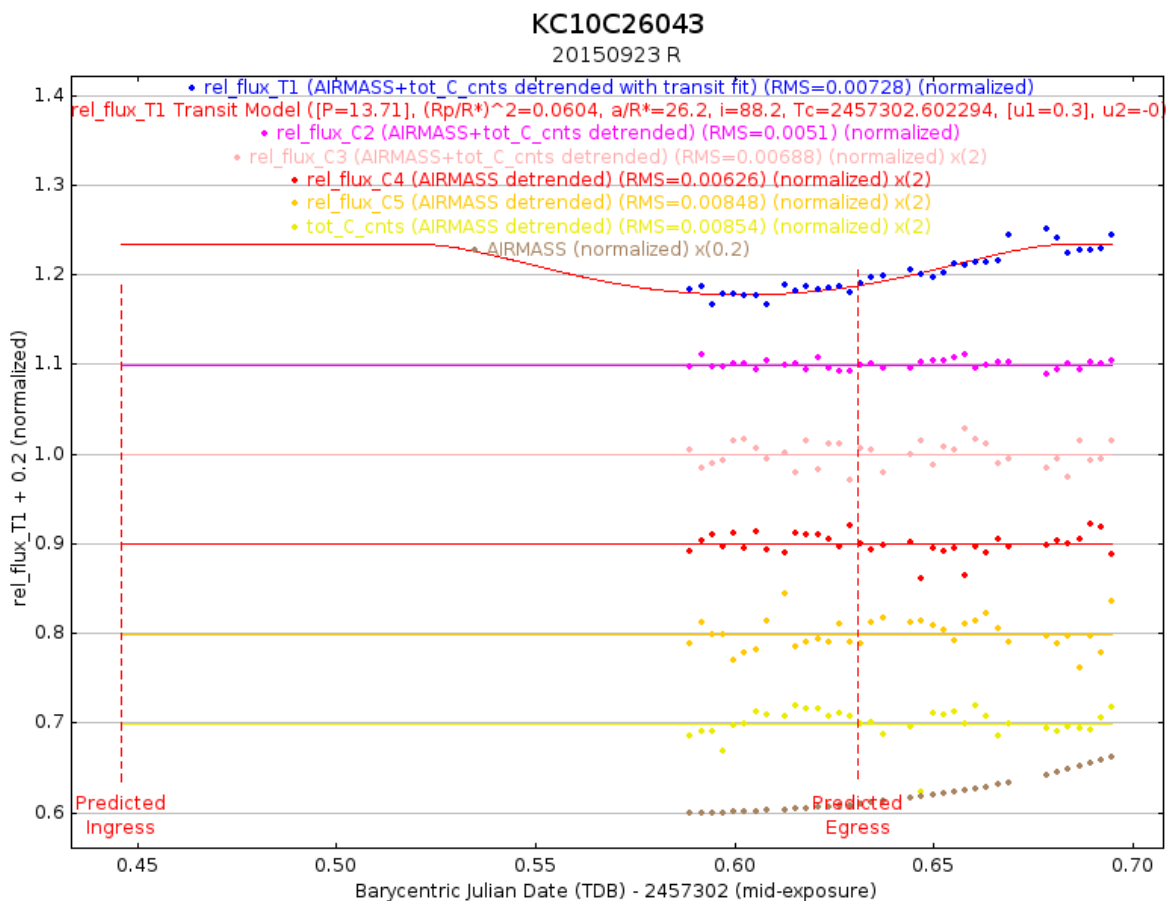
Figure 3.7 This data is good, but more will be needed to get more information on the star

3.7 KC11C006639

Finally we talk about KC11C006639. This figure was also foolishly left with the wrong heading so please be aware of that when you examine Figure 3.8. First the reason some stars seem to be ploted twice is because both the R and V band observation were plotted together. This was not on purpose, but was discovered recently as an issue. Another issue is that a star we selected for comparison has decreasing flux with airmass. Having said that, from looking at figure 3.8 it does seem to have a curve. The issue that we see with this is that it also seems to trend together with the airmass and the stars which had decreasing flux. This is not a large decrease in light. With

Astroimage J we noticed that it often will find a curve, but this drop in light is not consistent with that of our transiting planet. In the case of KC11C006639 we find that this is most likely due issues with high air mass and one the selected comparison stars. This star definitely needs be analyzed again, but with new comparison stars.
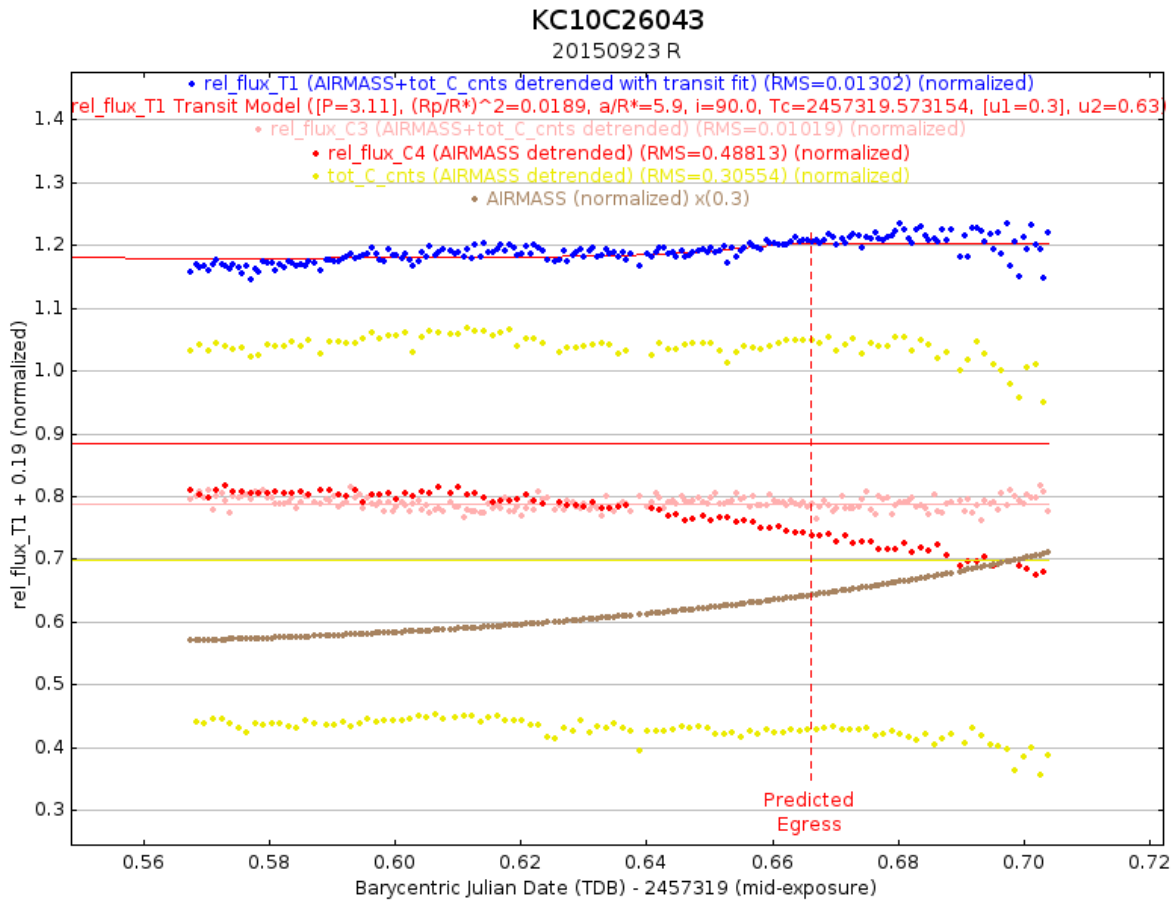

Figure 3.8 The trend seems to match that of the increasing air mass.

Chapter 4

Conclusion

4.1 Summary

We have looked at several different aspects of finding exoplanets and the process we have used to discover them. Our focus was on supporting the KELT team and their method for finding exoplanets.

While there was much left open to be done here we feel that anyone wanting to pick up on this work would be able to do so after reading this article. We also recommend reading the AStroimage J user manual found at $http://www.astro.louisville.edu/software/astroimagej/guide/AstroImageJ_{U}ser_{G}uide.$ in order to better understand how to use the program.

4.2 In the Future

Still there is a lot of work to be done on these stars. Several successful observations need to be done. If after many successful observations we do or do not see transits we can then determine for sure if there is a transiting planet or not.

The data that was unable to be successfully processed in Astroimage J is still contained on an

external hard drive. Our focus will be to make sure we get meaningful curves out of the data. If the data is not useful then we also plan on passing this information forward so that we can focus on getting better data.

Bibliography

Pepper, J., Pogge, R. W., DePoy, D. L., et al. 2007, PASP, 119, 923

Stetson, P. B. 1987, PASP, 99, 191