Detecting Exoplanet Transits with the LDST

Ivan Spirov,[1]*
[1] Faculty of Science and Engineering, University of Groningen, Groningen, Netherlands
[2] Honours College, University of Groningen, Groningen, Netherlands

24 March 2024

ABSTRACT

This research paper explores the feasibility of observing exoplanet transits using the Lauwersmeer Dark Sky Telescope (LDST) and investigates the key factors influencing successful observations. Exoplanet transits offer valuable insights into exoplanetary systems, and this project aims to detect and study these transits while expanding our knowledge of the LDST's capabilities. The methodology involves candidate selection based on star brightness and transit depth, followed by telescope setup and data collection. The data processing techniques include noise reduction through aperture and annulus corrections, resulting in lightcurves for each observed transit. The success of the observations is assessed through a chi-squared test, comparing the likelihood of continuum and transit models. It was shown that exoplanet transit observations are possible using the LDST. The results demonstrate successful observations of two exoplanet transits, highlighting the significance of transit depth and star brightness. The choice of broadband filters, the capture of flat frames, and favorable weather conditions are identified as important factors for successful observations. This research contributes to our understanding of exoplanetary systems and provides insights into the feasibility of observing exoplanet transits using the LDST.

Key words: Exoplanet transits – Observations – Lauwersmeer Dark Sky Telescope (LDST) –Exoplanetary systems – Candidate selection – Star brightness – Transit depth – Telescope setup – Data collection – Data processing techniques – Noise reduction – Lightcurves – Chi-squared test – Broadband filters – Flat frames.

1 INTRODUCTION

Exoplanet transits, the phenomenon of a planet passing in front of its host star and causing a detectable decrease in brightness, provide valuable insights into the properties of exoplanets. Observing these transits offers opportunities to study exoplanetary atmospheres, orbits, and sizes. This research project aims to investigate the feasibility of observing exoplanet transits using the Lauwersmeer Dark Sky Telescope (LDST) and determine the key factors influencing successful observations.

By investigating the feasibility of observing exoplanet transits and identifying the crucial factors for successful observations, this research project contributes to our understanding of exoplanetary systems and expands the capabilities of the Lauwersmeer Dark Sky Telescope. The subsequent sections of this paper delve into the methodology, data processing techniques, and results obtained from observing select exoplanet transits.

1.1 Project Aim

The primary objective of this project was to undertake a comprehensive investigation into the feasibility of observing an exoplanet transit. While it is theoretically plausible to observe such a phenomenon, the goal was to either succeed in detecting a transit or to show clear proof that such a transit was impossible. From the beginning, the biggest issue would be to overcome frame-to-frame noise in order to detect fine changes in luminosity. Factors that complicated the procedure were clouds, ambient light and residual sunlight. To that end multiple methods computational methods were used to reduce said noise. A major question to be answered in this project was which properties of an exoplanet transit were most vital in carrying out a successful observation. The LDST is capable of resolving objects with apparent magnitudes of nearly 18, meaning the range of stars was quite large, so it is important to know which transits to favor over others.

2 METHODOLOGY

The acquisition of data for this project is separated into two primary periods - direct observation, where setup for and execution of the observation take place, and data processing, where the raw data is carefully analyzed.

2.1 Observation

While simple in principle, observing an exoplanetary transit has a few caveats that play a crucial role in getting quality data. The process itself starts with picking a suitable candidate star, which will be observed for the transit of a local planet.

* E-mail: i.spirov@student.rug.nl

Star	Date	Magnitude	Visible Shifts
LP 141-14	19.05.2023	17.6	2
BD+66 911	19.05.2023	10.3	2
Qatar 8	18.04.2023	11.7	1
WASP-12	05.04.2023	11.5	1
HAT-P-54	04.04.2023	13.4	0
BD+46 2629	10.10.2022	9.8	1

Table 1. Attempted Observations. If both beginning and end of transit occurred during observation window, the visible shifts are 2. If only one of the two occurred, it is 1.

2.1.1 *Picking a Candidate*

The first step to any transit was picking a suitable candidate. Those transits were taken from the NASA Exoplanet Archive database, accessible visually through a Swarthmore website (Jensen 2023). The two primary criteria for a transit were sufficiently bright star and sufficiently large depth of transit. In general candidate stars needed to have magnitudes of 17 or lower and depth of transit of 10 parts per thousand to be considered.

Another consideration was whether the star could be observed at the beginning, during and after the transit has concluded. The minimal requirement was capturing enough frames prior to and after either the beginning or end of transit, so that a comparison could be made. In the ideal case both the beginning and end could be captured, so that a return to a continuum can be shown, but considering the length of some transits and the shrinking nights in Groningen, that was not always possible.

Table 1 shows a list of all candidates that have been observed throughout the project, with the date of observation, some general parameters.

Here visible shifts represents if the beginning or end or both were observed. The stars included above are the observations that were attempted, including a failed one (hence due to cloud coverage no shift could be even theoretically observed). With a candidate picked on an opportune night, the observation can be undertaken.

2.1.2 *Observation Procedure*

Many of the procedures followed during the observation phase adhere to standard ones carried out in any other project with the LDST. From a mechanical standpoint, it is recommended to deactivate dithering while ensuring continuous tracking. Optimal results can be achieved by positioning the target star roughly at the center of the image. For this particular project, observations were conducted exclusively using mount tracking (at a sidereal rate), which can lead to the accumulation of minor errors over time. It is nonetheless invaluable when compared to the alternative of no tracking at all, but any future observers are advised to keep track of the position of the target star and if necessary readjust by slewing into position. Despite the use of flatfield frames in data reduction, it is still preferable that the star stays in the rough middle of the frame to avoid errors due to optics. The successful implementation of an autoguider in the future would be indispensable for this project, particularly during long transits.

From a sensor standpoint, binning exposure time and filter had to be adjusted depending on the star. Two crucial factors in this decision-making process are the star's color and brightness. For bright stars, large binning is advised in order to remove as much noise as possible. A broadband filter should be selected that best matches the color of the star. In cases of dimmer stars Blue and Lum filters were preferred (as shown in results). Exposure time should be as long as permissible, again to reduce noise, while avoiding overexposure. When deciding on exact values, observers ensured that in test frames, the peak of the star's brightness was no larger than 50000 counts. If the transit has already begun and the observation aims to detect only the increase in luminosity, then that benchmark was lowered to 30000. For dimmer stars, the binning was set to be as large as possible, while still ensuring that a reasonable array of output pixels were dedicated to the target star. If an aperture with radius 2 could not be drawn over the star, binning needed to be increased. While some observers may be tempted to increase the exposure time arbitrarily until reaching good signal-to-noise ratio, the exposure time in most cases should not exceed 90 or at most 120 seconds. Otherwise the aforementioned tracking issue becomes apparent as stars begin to drift within the same frame, sometimes at a risk of overlapping. In those cases it is recommended to either use the Blue filter (it being the broadest of the LDST RGB filters) or the Lum filter (the broadest possible setting on the LDST). With those settings, even objects of magnitude 17.3 can be resolved (Gzib et al. 2023).

After the telescope settings have been set and the standard LDST procedures followed (taking of flat, dark and bias frames) the collection of data can begin. As mentioned before, corrections to the position of the star may be necessary. It is integral that a sufficient number of frames before and after each change in luminosity are taken. To that end it is also acceptable to begin data collection before astronomical twilight, as data reduction can to an extent reduce the effects, whilst gaining a greater insight.

2.2 Data Processing

The data processing is the most deceptively difficult step of this project due to the seemingly many routes for getting results. While the initial data reduction is straightforward, the subsequent specific steps followed are critical and can determine the success or failure of the observation. Therefore, meticulous attention to detail during the data processing phase is essential to ensure the acquisition of accurate and meaningful results.

2.2.1 *Initial Steps*

Owing to the reusability of code and the similarity in attaining a lightcurve with the variable star project, an extra step was undertaken (and is recommended to be undertaken by future observers) to ensure that data reduction is satisfactory.

The initial data reduction is identical to other projects - bias, dark and flat frame corrections. Alignment of the frames was done due to the aforementioned drift, but is not essential. It is important that the frames are kept separately. A median may be taken for the purposes of magnitude measurement via standard stars, but the primary goal of this project is to show that the detection of a transit is fundamentally possible.

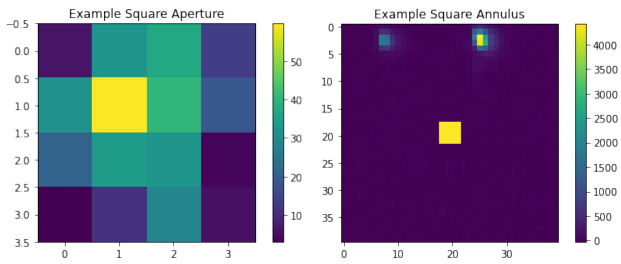


Figure 1. Example Square Annulus and Aperture of Star. Aperture is marked as a square within annulus. In both the same star is in the center. The dominant stars in the annulus are not the focus, but the reason, why this noise removal is done.

2.2.2 *Noise Removal*

Once an array of reduced frames is created, one can begin work on the lightcurve. To ensure reasonable frame-to-frame noise reduction, this project also created a lightcurve of YZ-Boo via data, which was collected by Crawford et al. (2023)[1], from the Blaauw archive (Kapteyn Institute 2023) using the same procedure. In essence a few simple, but vital steps were taken. The first was identifying two non-variable stars, preferably of similar magnitude as the candidate star, visible in each frame. Then, each frame has to have its global background noise removed. It normally the best measure for that is the median value of the frame. With the background noise value chosen, that value may be subtracted from the overall image. This is to be done on each frame. That may be insufficient for complete noise reduction however.

The next step is taking an aperture around each of the three stars on every frame as well as an annulus of a larger radius. An initial value for a datapoint for each star is then taken by summing the values within the aperture. It is recommended to use the photutils library in order to take circular apertures, but in cases of trouble with the library, a square aperture via simple python slices would be sufficient. Afterwards the total number of pixels within the aperture should be multiplied with the median value within the greater annulus. That is the correction value which is then subtracted from the initial signal value for the star. That step should be repeated for each star within each frame. The final value of a given datappint is given as such:

$$C_f = \sum_{i}^{n} \sum_{j}^{m} (D_{ij} - B) - n * m * median(An)$$

Where n and m are the dimensions of the aperture, D is the data within the aperture, B is the global background noise and An is the data within the annulus.

If the frames have been previously aligned, this step becomes much simpler, as the same apertures and annuli may be used for all frames. An example aperture and annulus are shown on Figure 1. Note that despite the presence of much brighter stars within the annulus, the procedure still works. That is because the median value is taken, which will not take the value of the large stars if annulus is large enough. Further, the effect of nearby bright stars is the exact reason this operation is necessary.

[1] The data was initially gathered for Observational Astronomy (OA) related purposes, but its significance extended to this project. The data collection process for all observations listed in this project was identical, as the supervising TA for said projects is the author of this paper.

2.2.3 *Further Noise Removal*

It is possible that the frame-to-frame noise is still too large. To that end two procedures to reduce it are possible. One would be averaging groups of 2, 3 or even 4 frames. This is recommended only if the noise is indeed too large and the transit is long (over 20 frames). This can only be done if the frames have been aligned, as otherwise stars would drift and summing or averaging would result in unusable data. If that is the case, then the mean of datapoints can be done with the completed arrays.

The second option is a 'smoothing' algorithm that is run over completed datapoints. It is important to note that this algorithm provides clearer patterns, but destroys precision and gives data that can not be used for further scientific purposes. It is simple in principle - taking an average around a pivot point. For example, if the smoothing has a radius of 2, then the value of datapoint N is the mean of datapoints N-2 to N+2. This way the number of output frames is larger than simply taking averages (as these means overlap), thus giving more clear patterns at the expense of rigor.

2.3 Lightcurve

At this point 3 arrays of values have been created - one with the photometry values of the candidate star and the two accompanying stars[2]. For the sake of preserving luminosity, it is also recommended to take a median value of the correcting star, though if simply observing the transit's occurrence is the goal, that is not necessary. For complete precision one would take the median of all frames, then perform photometry on the final frame and use that as the true renormalizing value. The lightcurve can now be taken. The array of the transit star is now divided by the array of one of the accompanying stars, henceforth called the normalizing star. The third array is also divided by that of the normalizing star. If a median value of the normalizing star has been taken, both resultant arrays are multiplied by that as well. The result is two arrays, one of the transit star and another of a non-varying star, both normalized such that they don't vary from frame to frame. This procedure is identical for a variable star as well, but requires greater precision for exoplanet transit, especially with lower transit depths.

2.4 Real-Time X-Axis Plotting

A small, but important part of plotting lightcurves is setting the X axis to real time. For that purpose log sheets and frame metadata serve as invaluable resources. When plotting the datapoints, they should be plotted against a custom array that includes the corresponding recording time of each frame. That way if for one reason or another (such as taking standard star fields) the lightcurve is interrupted, that would be reflected in the final data (such as in Figure 2).

3 RESULTS

The final goal of the project is to find if the detection of an exoplanet transit is possible. To that end, the lightcurve was plotted, where ideally the transit would be clearly visible. However, due to noise, patterns can emerge from nothing. To confirm the likelihood of a transit, reduced chi squared test was run over all transit lightcurves with two functions. One function was a simple constant value (set

[2] For added precision one may use more stars for correction, especially to ensure no variation in the correcting star.

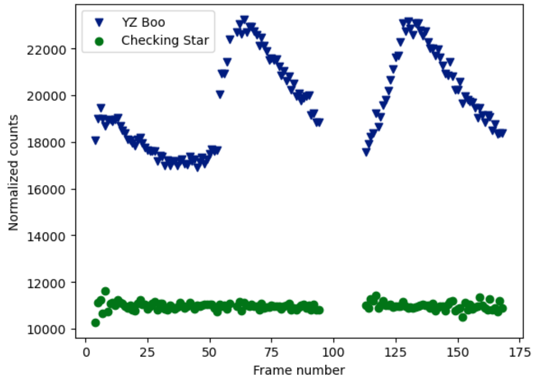


Figure 2. Lightcurve Near YZ Boo. YZ Boo (blue triangles) curves clearly, while non-variable (green dots) does not. Gap present due to standard star fields. Curves less defined and more noisy near sunset.

to the mean value, i.e. the most likely single value). The second was a step function with a decrease in brightness equal to the predicted depth of the transit. A successful observation was therefore one, where the reduced chi squared test of the step function was lower than the constant.

3.1 YZ-Boo Lightcurve

As mentioned above, the methods for data reduction were first tested on YZ Boo, in order to confirm the resultant lightcurve is satisfactory. The final lightcurve is shown in Figure 2. The gap seen in the middle is due to an interruption, required to capture standard stars for a dedicated variable star project. Observation began before nautical twilight, thus the first 18 frames had much more ambient light, hence the less defined shape of the lightcurve.

3.2 Transit Lightcurves

After reducing the data from the observations lightcurves of each candidate star were made. To ensure that, apart from visual appearance, the patters observed are indeed more likely to be transits than not, a reduced chi squared test was run for each of the well-observed transits. The following two functions were compared:

$$f_1(t) = m$$

the continuity function, being a constant value equal to the mean of all data points (the most likely single value);

$$f_2(t) = \begin{cases} m' * \frac{\text{depth}}{1000}, & \text{if } t_1 \le t \le t_2 \\ m' & \text{otherwise} \end{cases}$$

the transit function.

The transit function used predictions to set the beginning and end of each transit (t_1 and t_2. The upper bound value of the transit equaled the mean of all non-transit values, while the lower value was simply decreased by the predicted depth of the transit.

The results of the tests were compiled in Table 2. The transits with lower χ^2_ν of the transit model than that of the constant model value are considered successful observations. The two successful observations were both conducted in the same night. Graphs of the well-observed transits can be seen on Figures 3-6, where normalized counts (Y axis) are plotted against frame number. In the case of BD+66 911, 3 frames are absent, due to an issue with the telescope mount, which rendered them unusable[3]. Normalized counts still do not pertain to precise magnitude measurement as this was outside the scope of this paper. Simply, the median luminosity of the normalizing star was taken and multiplied back into the otherwise fractional result of dividing the counts of two stars.

Star	Transit Depth (ppt)	Transit χ^2_ν	Constant χ^2_ν	$\Delta\chi^2_\nu$
LP 141-14	566.5	6.79	15.92	-9.13
BD+66 911	21	57.25	75.82	-18.57
Qatar 8	12.6	23.3	26.25	-2.95
WASP-12	17.1	40.57	26.03	14.54

Table 2. Select Transits Likelihood. Reduced chi square taken for both models. The more negative the delta chi, the more likely the transit is.

Star	Transit χ^2_ν	Constant χ^2_ν	$\Delta\chi^2_\nu$	Transit $\Delta\chi^2_\nu$
LP 141-14	3292.09	62.03	3230.06	-9.13
BD+66 911	21.25	9.55	11.71	-18.57
Qatar 8	177.59	82.82	94.77	-2.95
WASP-12	107.75	59.64	48.11	14.54

Table 3. Select Transits Continuum Likelihood. Same procedure for transits was done for checking stars. Positive chi difference shows unlikely transit (likely non-variable).

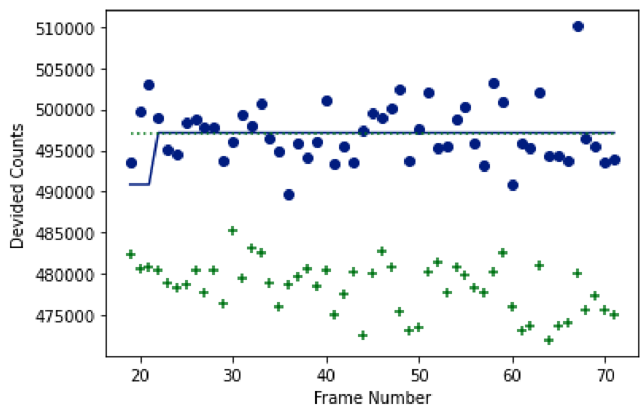


Figure 3. Graph of WASP-12 b (blue dots), compared to scaled non-variable (green pluses). Straight blue line is transit model, green dotted line is continuum model.

4 DISCUSSION

Having successfully observed the transits of two exoplanets, the primary objective of this project has been accomplished. The following section will now shift its focus to highlight the key factors that significantly impact the probability of achieving successful observations.

[3] This is a reoccurring issue where the telescope suddenly slews away with no input. A hypothesis between students is that the issue is caused by tracking via the mount. Upon reaching the limits of the mount, the telescope slews away. Regardless of the true cause, it stands as another reason for observers to remain vigilant and keep a close eye on the telescope.

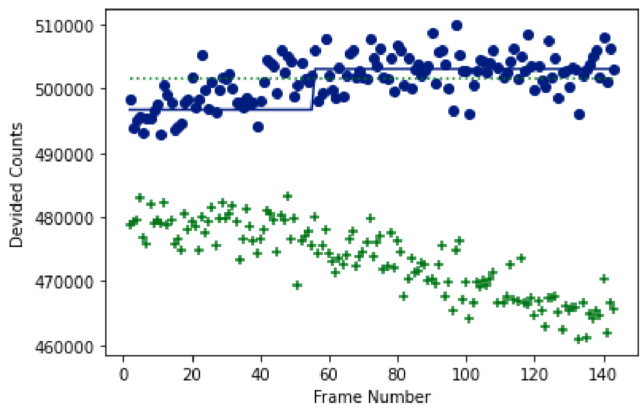


Figure 4. Graph Quatar-8 b (blue dots), compared to scaled non-variable (green pluses). Straight blue line is transit model, green dotted line is continuum model. Due to lack of flats, neither curve exists correctly. Higher likelihood of transit is coincidental.

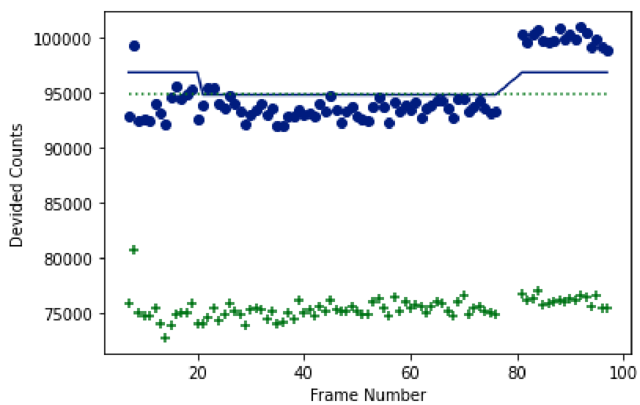


Figure 5. Graph Kelt-23 A b, exoplanet of BD+66 911 (blue dots) and scaled checking star (green pluses). Straight blue line is transit model, green dotted line is continuum model.

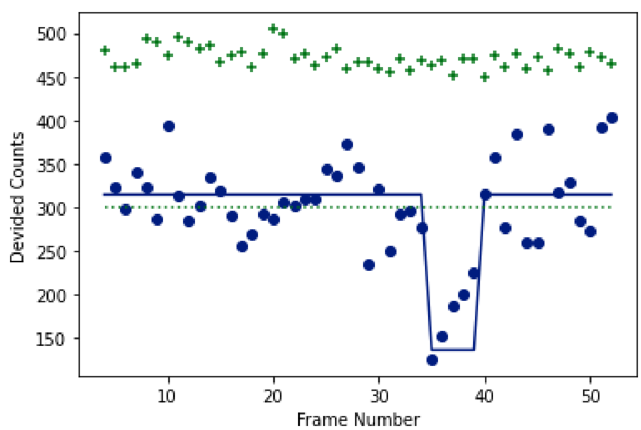


Figure 6. Graph of LP 141-14, exoplanet of WD 1856+534 (blue dots) and scaled checking star (green pluses). Straight blue line is transit model, green dotted line is continuum model.

4.1 Star Properties

The successful observation of both LP 141-14 and BD+66 911 on the same night allows for a more intrinsic comparison. That is because the flat frames for both were recorded together (one brighter using RGB and the dimmer Lum frames).

It must be noted that both successful observations were performed on transits of depth more than 2%. While objectively low and difficult to detect, twenty parts per thousand are comparatively high within the set of potential transits. That is why planning is essential for this project. From both successful transits it is clear that either the depth of the transit must be notably deep (like in the case of LP 141-14) or the star must be comparatively bright.

The choice of stars is increased in the case of the LDST, since detection of dim objects is possible, so stars up to magnitudes of 17.6 (like LP 141-14) are manageable. In this project, it is advisable to prioritize identifying transits with a substantial depth, ideally with both the beginning and end of the transit visible. Only after identifying such transits should candidates be sorted based on their magnitudes. By focusing on transits with significant depth, the project can maximize the chances of obtaining higher-quality data.

The length of the transit is also an important consideration. Prolonged transits are more susceptible to unforeseen challenges such as rain, clouds, adverse weather conditions, and ambient light, all of which can hinder a potentially successful observation. Conversely, transits that are too short are more difficult to capture and may be less discernible amidst the noise. Given the opportunity to select a transit, it is advisable to opt for one that spans approximately an hour in duration. This timeframe strikes a balance between allowing sufficient data collection and minimizing the risks associated with longer transits.

4.2 Observation Prerequisites

The choice of a broadband filter plays a crucial role on this project. It was expected the the Blue and Lum filters will be best utilized, due to allowing more light through, thus more signal. This is especially instrumental with dimmer stars. During this project all filters were tested, thus meaningful insight was attained. Furthermore, a transit has been detected with every filter, which can be meaningfully used, namely R, G, B and Lum. The color filters were used in observing BD+66 911, while Lum was utilized for the especially dim LP 141-14. The use of all three broadband filters for the former were due to it being recorded in OA by Gusi et al. (2023). Nevertheless, the transit is visible on all filters, but is most clearly visible in blue[4] as seen on Figure 4.

The relative noisiness in red and green confirms that blue is indeed the best candidate out of the standard broadband filters for such observations. This is likely due to the fact that a broader filter allows more signal through, thus overpowering noise that may become deciding frame-to-frame. This is especially clear near sunset. Observation of the star began before astronomical twilight (similar to YZ Boo), thus noise removal at the beginning of the observation becomes more difficult, while patterns become more faded. It still serves to portray the effects of different broadband filters. It is recommended for observers that aim to detect a lightcurve to use the Blue filter or even Lum to attain a 'grey' lightcurve. It should also be noted that the

[4] It is for this reason that the lightcurve extends to blue past frame 46. It was decided that more precision in the most crisp filter takes priority over color, since any calculations about the color of BD+66 911 could be done off the initial set of frames.

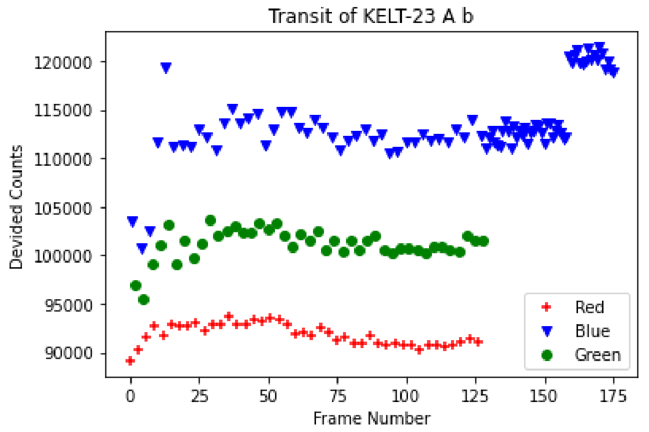


Figure 7. RGB Lightcurve of BD+66 911. At first blue (triangles), red (pluses) and green (dots) are taken in sequence. Near end (before second shift) only blue frames were taken for precision.

color lightcurves seen on Figure 4 are not to scale with each other. That is because the normalizing star is not grey and its color needs to be accounted for final scaling. That is also the reason the lightcurve for blue is between those for green and red, which would otherwise not make sense.

While flats are generally important for observations, it must be stressed that they are essential for this project. This is because when data reduction is not done properly, later methods for noise reduction simply do not work. This is best shown in the lightcurve of Quatar-8. Due to beginning observation late, capturing flat frames was not possible when observing Quatar-8, meaning data reduction skipped the use of flats. The resultant data could not be properly reduced and clearly stands out on Figure 4 as being the least clear, not even presenting a well-defined continuum. That is due to the aforementioned drift, because the areas with increased/decreased luminosity move over the stars that are observed, causing the unexpectedly curled lightcurves. This project hinges on flats, which is why if not possible to capture on the date of observation, new ones should be taken as soon as possible. Furthermore, if dome flats could be attained in this project, then it would allow for more flexibility with other projects, since capturing flats at night after switching with another group would be possible.

Another crucial consideration for this project is weather conditions, which is a standard consideration applicable to all projects but can significantly impact the success of transit observations. As mentioned above, this project is susceptible to issues with noise. That is why clouds, even thin ones, can present major issues. That is especially important if the predicted transit for the given night is a long one. Similarly, ambient light can have a catastrophic effect on the observations. As evidenced by the sunrise sections of both YZ Boo and BD+66 911, the patterns in a light curve can become obscured or completely obliterated. Therefore, it is highly recommended to commence this project as early as possible to take advantage of dark spring nights and mitigate the detrimental effects of clouds and ambient light. Initiating the project promptly will optimize the opportunities for successful and reliable transit observations.

5 CONCLUSION

This research project aimed to investigate the feasibility of observing exoplanet transits. The primary objective was to either detect a transit or provide clear evidence that such observations were impossible. The project faced challenges related to frame-to-frame noise, which required the application of various computational methods to reduce the noise.

Candidate selection played a crucial role in the project's success, focusing on bright stars with significant transit depth. The availability of the star for observation before, during, and after the transit was also considered. The methodology involved adjusting telescope settings, capturing frames, and collecting sufficient data points before and after the transit.

Data processing was a challenging yet essential aspect. Initial steps included bias, dark, and flat frame corrections, followed by noise reduction techniques. Aperture and annulus corrections were applied to remove background noise, ensuring clearer patterns in the lightcurves. Successful observations were identified by comparing chi-squared values of constant and transit functions.

The project successfully observed transits of two exoplanets, demonstrating the feasibility of detection. The depth of the transit and star brightness significantly influenced the probability of successful observations. The choice of broadband filters, capturing flat frames, and favorable weather conditions were crucial factors. Overall, this research project provides valuable insights into the feasibility of observing exoplanet transits, emphasizing the importance of candidate selection, precise data processing, and optimal observation conditions.

ACKNOWLEDGEMENTS

This project would not have been possible without the assistance and guidance of Jacob Noel-Storr, PhD. Similarly, guidance from Dirk van der Geest proved invaluable early on in the project. The use Lauwersmeer Dark Sky Telescope was instrumental to this project. Data for the successful observation was initially meant for the purposes of Observational Astronomy and subsequently downloaded from the Blaauw data archive.

DATA AVAILABILITY

All data used in the project is available in the Blaauw Observadoty Data Archive. The Kapteyn Institute (2023) has made it accessible directly by RuG students and staff. All raw data consists of fits files and data log sheets.

REFERENCES

Crawford R., Meulenaar V., Rodríguez M., Rahman A., 2023, Private Communication
Gusi A., Huisman Q., Cabrer N. Q., 2023, Private Communication
Gzib D., Sebert G., de Hoog Bouthoorn I., 2023, Private Communication
Jensen E., 2023, Find Exoplanet Transits, https://astro.swarthmore.edu/transits/transits.cgi
Kapteyn Institute 2023, Blaauw Observatory Archive, https://sites.google.com/a/rug.nl/blaauw-observer/archive/data-archive

APPENDIX A: STUDENT GUIDE TO DETECTION

There are four major parts of this project, which you have to ensure are accounted for. This project requires precision, so mistakes on any of these steps may be irreparable.

A1 Planning

Before the date of observation you must be acquainted with the target star. It is likely that course organizers will be working on the schedule, but keep in mind your project is one of the most time-sensitive and so you too must keep in touch. The candidate stars can be found on https://astro.swarthmore.edu/transits/transits.cgi. You need a star of considerable (above 15 ppt) depth and visible for the LDST magnitude (under 18). It is possible that your observation TA is not famılliar with the project, so make sure you know which star you are looking for.

A2 Observation

On the day of the observation you need to be sure that a few things are done correctly. You need to decide (discuss with your TA) which filters you will use. If the star is bright enough, you can use RGB and attempt to capture the transit in color (this will give you more information later on). If the star is dim, use the Lum filter.

Also discuss with the observation TA on what binning you will use. It is recommended you use maximum binning (4), but it may need to be reduced if the star is too faint. Those are all important to discuss with your TA prior to capturing flat frames. Data reduction will hinge on flat frames, so not capturing the proper ones may be catastrophic. Capture flats of the same binning and filter as you will use later in the night. Same applies for dark and bias frames, but those can be captured later on in a case of a mistake.

After setting the telescope up and finding your target star, settle on exposure time with your TA. The dimmer the star, the longer the exposure time, but be mindful of drift. If the LDST has an autoguider when you observe, disregard the rest of the paragraph. If you are unsure, ask Jake or your TA. If it does not, then you should be careful how long your exposure is, as if it is too long, the stars will begin to drift during the frames.

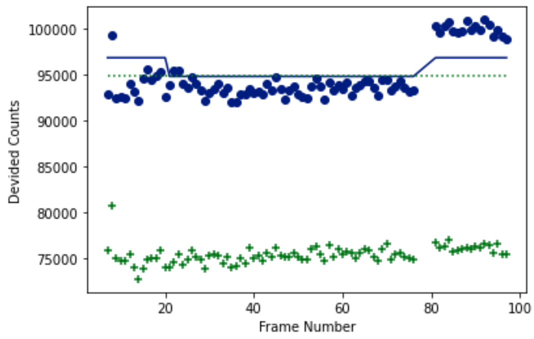
If there are clouds on the day of the observation, keep an eye on DS9 for large increases in noise and write them down in the log sheets. Similarly, take note of clouds, even thin ones that the telescope can see through. This will help you dispel false positives later.

I strongly recommend writing down the pixel coordinates of your target star on the log sheet (especially if it is dim), eg. 909,235. On the night of observing you might think it is very clear where your star is, but chances are you will be reducing your data weeks later. In case you lose your star, open its simbad page and upload one of your frames to https://nova.astrometry.net/. From there you will need to carefully find which star is your candidate.

A3 Data Processing

With your data downloaded, make sure to carefully reduce it as with any other project. Proper use of flat frames is essential. It is recommended to align the frames, but it is not essential. If the LDST has an autoguider, this step is already done for you. The last step to do to each frame is taking off the global noise. To do this, simply find a noise value and subtract it from the whole frame. This value usually corresponds to the median over the entire frame.

With the processed data before you, find at least two other stars



that you can use of normalization. You need them to be non-variable, so you might need to look them up in astronomical catalogues. You will then do the following to EACH star, resulting in 3 (or more) data arrays.

Take an aperture around the star. It can be circular (using photutils) or square (a simple 2D slice). Take the sum over the aperture (your signal). Then take a large annulus (again circular or square) around the aperture. Take the median within that annulus, multiply it by the number of pixels within the initial aperture and subtract it from the signal. This number is your datapoint for the given star at the given frame. Repeat for every frame. If the data is aligned, this becomes much easier, because you can reuse apertures in a for loop.

With the three arrays ready, pick one as your normalization star. Divide your transit star array by the normalization one. Do the same to the third array. If everything was done right, the third array should present a roughly constant value line and the transit array should show a transit like the one below. The Y axis will be a fraction. To get an actual number you will need to multiply by the 'true' counts of the normalizing star. The proper way to do so would be to allign all frames, take the median, then to the aforementioned steps to get the value over the same aperture. The faster and less proper way would be to simply take the median from your normalization array. Nevertheless, to convert into magnitudes (as you may be expected in the project), you will need to use standard stars as other groups will. If you use color filters, keep an eye on the errors that come from normalizing with a star that likely has a different color from your candidate star.

If you have issues in getting the transit, try to play around with the sizes of the annulus and aperture. If it is still too noisy frame-to-frame and the transit is supposed to last for a while, you can sum every n frames to try to get a more stable average.

A4 Proving The Transit

To ensure that the transit is not a trick of the eye, you should run a chi-squared test on your data. Make two model functions and compare them with your data. One should be a constant value (the mean), while the other should be the ideal case transit - a continuum with a dip. Run a chi-squared test on both. If the reduced chi squared for the constant is lower, then your transit is not believable.

A5 Further

You may be expected (or be encouraged) to expand the project by getting the change in magnitude of a certain color, get a final image and much more (our team is creative). Consult your TAs and check the descriptions of other projects, since some of these parts are similar.

This paper has been typeset from a TEX/LATEX file prepared by the author.