

A Closer Look at Potential Exoplanets Targets from the Nooitgedacht Observatory

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Abstract. Surveys like KELT and TESS search for transiting extrasolar planets, and have found many potential candidates. The optical telescope at the Nooitgedacht Observatory is ideal for follow-up observations of these candidates, and to collect more data of specific promising candidates. Candidates that are suitable for observations were identified. The suitability of candidates depends on the magnitude of the host star, the decrease in magnitude during the transit, and the angle at which the star is located when the transit begins. From numerous observations, the capabilities of the optical telescope at the Nooitgedacht Observatory are established and refined. The data collected from the suitable candidates was processed using aperture and differential photometry and compiled as a light curve. The light curve was then analyzed to study the transits and compared them to published data obtained from previous observations. We present the light curve of exoplanet WASP 80-b and conclude that it is the ideal type of exoplanet to observe from the Nooitgedacht Observatory.

1. Introduction

Since the discovery of the first exoplanet, 51 Pegasi b [1] the interest in extra-solar planets has increased exponentially, as well as the discoveries thereof. As of August 2021, 5071 exoplanets has been confirmed by NASA [2]. Multiple space based surveys like NASA's TESS (Transiting Exoplanet Survey Satellite) and the Kepler space telescope is used to find exoplanets. Ground based surveys like KELT (The Kilodegree Extremely Little Telescope) and HATNet (Hungarian-made Automated Telescope Network) was also on the hunt. There are multiple methods of detection and confirmation. These methods include the transit method, the radial velocity method, gravitational microlensing and direct imaging, which are the four main methods used. In this project we use the transit method to observe known exoplanets and compare the data to published work and to determine the limitations of the equipment at the North-West University's Nooitgedacht Observatory.

2. Nooitgedacht Observatory

The Nooitgedacht Observatory is located approximately 35km outside of Potchefstroom on a farm in the Vredefort Dome at $26^{\circ}54'0.09S$, $27^{\circ}10'0.05E$ which is at an elevation of 1448m. This observatory was used for the observations for the duration of the project. The telescope is a Meade LX200 16" f/10 ACF Schmidt-Cassegrain. Its mirror has a diameter of 40.6 cm and a focal length of 4064 mm. This all brings about the telescope's resolving power of 0.285 arc-seconds. The mount that moves telescope is a Paramount ME German equatorial mount

controlled by TheSkyX software by Software Bisque. The main imaging CCD camera is the Quantum Scientific Imaging (QSI) 540wsi, with a field of view of approximately 15×15 arc-seconds. It has internal cooling and can take a color filter wheel. The guiding telescope that is used is the Williams Optics ZenithStar 70 mm Doublet ED APO. It is a refracting telescope with a focal length of 420 mm. The camera connected to the guide telescope is the Atik Titan, which has a field of view of approximately 30×30 arc-seconds. The guide telescope was mainly used for auto-guiding purposes.

3. Transit method

3.1. Overview

The movement of a planet when it first moves in front of the disk of the host star, until the planet leaves the disk, is called the transit. If an observer has a line of sight on the planet as it moves across the disk of the host star, the observer will see a decrease in the flux of the star. The transit method entails observing the host star and continuously taking images before the transit starts until after the transit ends. Using aperture and differential photometry the flux of the star is then obtained from each of the images. The value of the flux is plotted against time and the resulting graph is called the light curve, which shows the diminishing flux of the host star during the transit.

3.2. Selection of Targets

To acquire potential targets available for observation from the Nooitgedacht Observatory we used the Exoplanet Transit Database [3]. This database gives transit predictions that is visible from your location, as well as the variables of each exoplanet. These variables include the start time, end time and duration of the transit, the magnitude of the host star, the dip in magnitude of the star during the transit and it gives the angle between the horizon and the host star at the beginning and end of the transit. Due to limitations of the Nooitgedacht telescope there are three criteria the target needs to meet to be a good candidate for observation. The first criterion is the magnitude of the host star. The optimal range for the telescope is between 8 and 12. This range is an approximation because it also depends on the depth of the change in the host star's magnitude during the transit. This is the second criterion. The fainter stars need a larger depth to obtain usable light curves. The third criteria is the angle at which the transits starts and end. These angles need to be above 30 degrees, as a consequence of the telescope being located inside a building where the roof opens. From the horizon, this obscures about 25 degrees of the sky and the observation has to start at least 30 minutes before the transit start.

3.3. Image Capturing

When a target is selected, four types of images are taken - the light images and three types of calibration images. The light images are processed to obtain the the flux of the host star. We need to select an exposure time for these images to optimize the signal-to-noise ratio (SNR). The selection of exposure time is also important to prevent over-saturation or underexposure. The highest analog-to-digital unit (ADU) in the image must be below 75% of the saturation point of the imaging camera's detector. Prior to the start of the observation images are taken at different exposure times and then an exposure time is chosen where the SNR is lowest and the ADU is in the correct range. The position of the star also need to be taken into account. As the star moves during the observation the airmass will change, which will affect the apparent magnitude of the stars in the image and in turn will affect the the ADU of the images. From the information obtained from the Exoplanet Transit Database, the observation needs to start at least 30 minutes pre-ingress and end 30 minutes post-ingress.

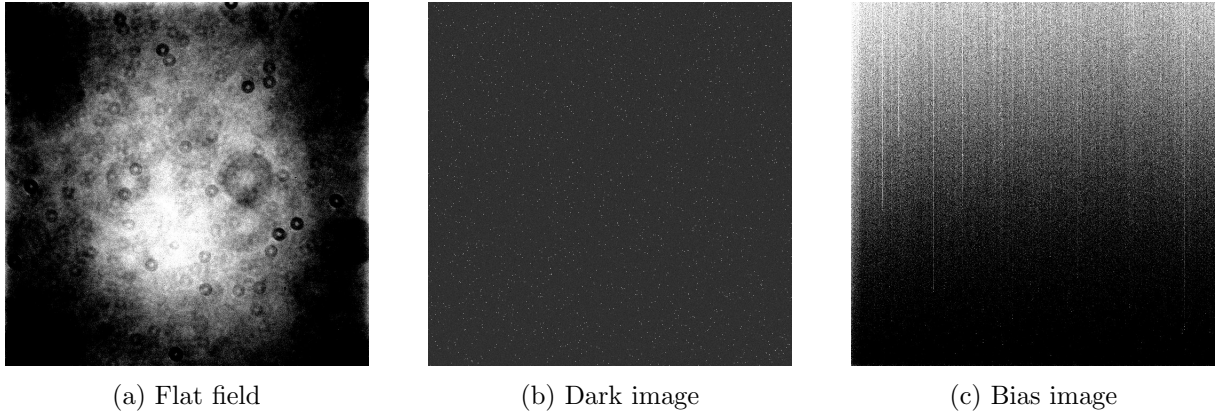


Figure 1: Example of calibration images taken on 27/07/2021 for WASP-80 b

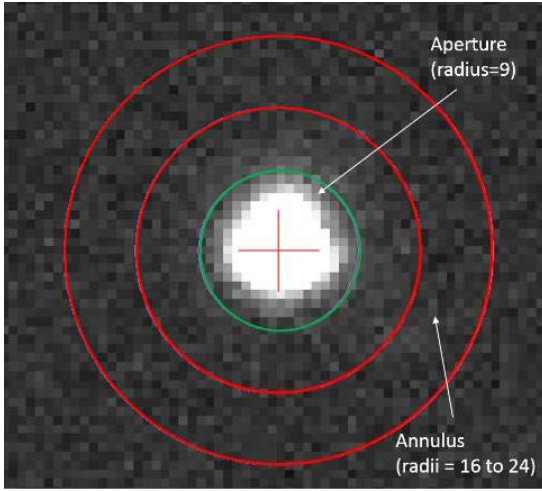
The first of the calibration images is called flat fields. These images are taken after sunset but before any stars are visible. These images are used to correct the light images to mitigate the effects of dust donuts (caused by dust on the equipment) and vignetting. The exposure times for these images must be short enough to prevent saturating the images. Dark images, the second calibration image, are taken after the observation in the same conditions as the light images, including the exposure time and temperature. These images are taken with the mirror of the telescope covered so no light can reach the camera's detector. These images capture any thermal noise due to the equipment and is used to remove the noise from the light images. Because every pixel of the camera is different, they read the incoming signal differently.

The final calibration image that needs to be taken is the bias. These are taken at a exposure time of zero seconds and with the telescope lens covered. These images capture any readout noise from the camera sensor and are taken after the observation. The three calibration images, shown in figure 1, is used to correct the light images during the data processing. At least ten images is needed for each type of calibration image are taken and combined together.

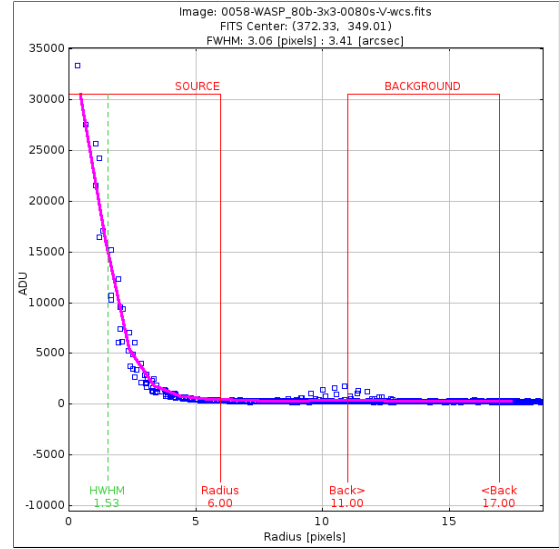
3.4. Image Processing

After the observation the images are imported to an application known as AstroImageJ (AIJ). This software is specifically used for processing and analyzing astronomical images, and light curve extracting by using differential and aperture photometry [4]. The images are processed in three different phases using AIJ, the preparation, calibration and differential photometry phase. In the first phase the light images are scanned through to look for any unusable images, this includes images where meteor or satellite trails are visible. These images are then removed from the data set. This is also where we check if a meridian flip has occurred.

The calibration phase is where the images are prepared for differential photometry. AIJ is used to correct the light images with the flat fields, dark and bias images. The calibration images are combined to create a master file for each type of image. The master files are then used to correct all the light images. After the correction the light images are also plate solved. By using a local install of astronomy.net, the star field in the images are compared to a database of star positions. This is done to determine the right ascension and declination of the center of the image. The plate solving is necessary because of misaligned images and drifting during the observation, it help AIJ during the next phase to keep track of the stars in the images throughout the processing.



(a) Aperture and Annulus drawn around a star



(b) Seeing profile of WASP-80 b

Figure 2

During the differential photometry phase, aperture photometry is applied to determine the flux of a star. When an aperture is drawn around a star, as seen in figure 2a, there is background sky contribution. To compensate for this an annulus is also drawn around the star, also seen in figure 2a. The ADU count in the annulus is used to adjust the ADU in the aperture and remove the contribution of the background. To obtain the values of the radius of the source (star) and the radii of the inner and outer annulus the seeing profile function of AIJ is used. This gives a graph as shown in figure 2b.

The flux of the host star also changes during the observation due to atmospheric extinction. To correct this comparison stars in the field-of-view are selected. It is important that these stars are not inherently variable and their magnitude is close to that of the host star. The aperture function is also applied to these stars, and their flux is adjusted to be constant. The adjustments made to flux of the comparison stars is then used to normalize the flux of the host star, to compensate for atmospheric extinction. The predicted ingress and egress points are added, the data prior and after these points are used to establish a baseline of the flux of the host star. AIJ then outputs a measurements table which is used to plot the light curves.

3.5. Model Fit

AIJ creates a model fit on the data, firstly it takes into account the predicted ingress and egress points of the transit and the radius and spectral type of the host star when creating the model. The model fit can then be modified by selecting certain detrend parameters to include in the model. These parameters are included or excluded to get the Bayesian Information Criterion value as low as possible for the best possible model fit[4]. This value is calculated as follow:

$$BIC = \chi^2 + k \ln N \quad (1)$$

Where k is the number of fitted parameters and N is the number of data points. When the best possible combination of detrend parameters are selected, the ingress and egress points of

the model are added to the plot. From the resulting light curve, the radius and composition of the planet can be inferred if certain variables are known. Assuming the flux from the planet is negligible and the host star and planet is spherical we have the following approximation [5]:

$$\Delta F \approx \left(\frac{R_p}{R_*} \right)^2 \quad (2)$$

Where R_p is the radius of the exoplanet and R_* is the radius of the host star and ΔF is the observed change in flux of the host star. AIJ provides the value of ΔF and if the radius of the host star is known we can approximate the radius of the planet using equation 2.

4. Results

WASP-80 b satisfied all conditions mention in section 3.2. The observation of this exoplanet was done on the 27th of July 2021 from 21:07 until 23:59 SAST. The host star has a magnitude of 11.881 and the a change in magnitude of 0.0310. This is a rather faint star, but the size of the change in magnitude made it a good target.

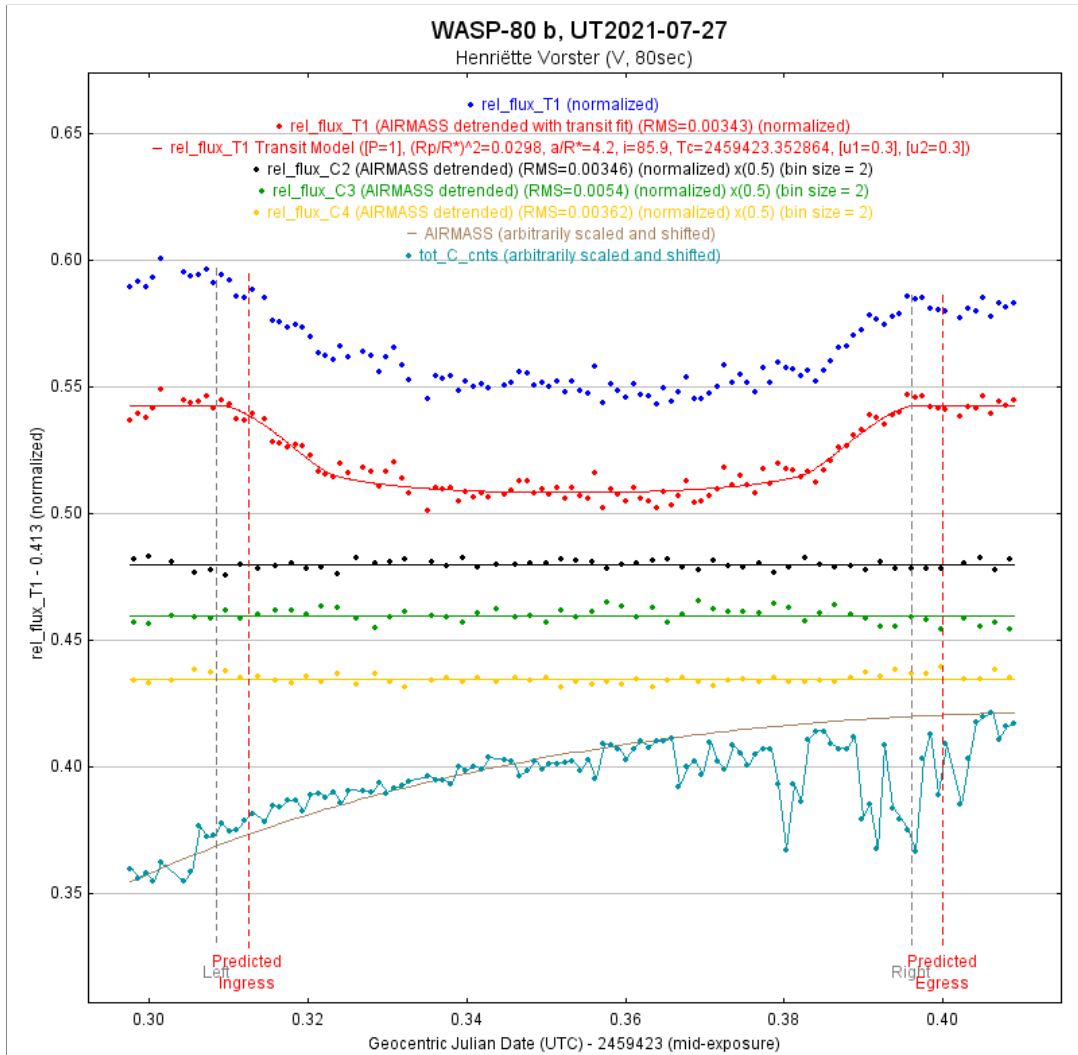


Figure 3: Plot for WASP-80 b, comparison stars and airmass, including the AIJ model fit

According to the Exoplanet Transit Database the transit started at 21:30 and ended at 23:36 SAST. We therefore had 23 minutes of data prior to and after the transit. The images were taken with an exposure time of 80 seconds, in the V-filter. It was three days after full moon, the humidity was at 50% and the temperature was at about 4°C. The light curve for this observation is given in figure 3.

This plot includes the normalized flux for the host star, the model fit for the transit, and the relative flux for three comparison stars, as well as the airmass throughout the observation paired with the total counts for all the comparison stars which is arbitrarily scaled. As can be seen from figure 3 the predicted ingress and egress times do not match that of the model, this can be due to various reasons. Because the moon was bright the night of observation the background sky contribution might have influenced the data. The observation also started only 23 minutes before the transit started, this means there is only 17 data points before the transit, which might not be enough to establish an accurate baseline for the flux, the same goes for the data points after the transit ended. The value for ΔF is given as 0.0298 and using the radius of the host star $R_* = 0.63 \pm 0.15 R_\odot$ [6]. We used equation 2 to calculate the radius of the exoplanet as $R_p = 1.058 R_{\text{Jupiter}}$. The radius of WASP-80 b was found to be $R_p = 0.95 \pm 0.03 R_{\text{Jupiter}}$ [7]. The radius calculated from the model is in close proximity to the published radius, but does not lie within the error margin given. This can be due to the same reasons given above.

5. Conclusions

We are capable of doing differential photometry at Nooitgedacht. We still need to process all the data taken throughout the project to conclude on the full limitations of the telescope at Nooitgedacht when observing exoplanets. WASP-80 b is a good candidate to observe from Nooitgedacht, and targets with similar attributes can be considered as good exoplanets to observe.

References

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