Detection of Exoplanets based on the Transit Method

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Abstract. Exoplanets are planets orbiting a star other than the Sun. These exoplanets may exist in many different forms, such as a hot Jupiter and super earth. Detecting is the first step to further studying the properties of these exoplanets. In this paper, based on data of star Qatar-1 gathered from July 22nd 2022, a light flux curve is developed during the period of 04:28 - 07:01 UTC through which the star is observed. The presence of an exoplanet, presumably Qatar-1b, is revealed in the analyzing results of the collected data, showing the validity of the transit approach for exoplanet detection. By using this approach, exoplanets planets can be discovered for further research in regards to potentially habitable and/or resource-rich exoplanets.

Keywords: Exoplanets, stars, data analysis.

1. Introduction

Exoplanets are defined as planets that are beyond our solar system. Most exoplanets tend to orbit around stars, however, some exoplanets are free-floating in space, which are also known as rogue planets (Butler et al., 2006 [2]). Since the first detection of an exoplanet around a pulsar over 25 years ago, the realm of exoplanet detection has been constantly expanded. There have already been many missions dedicated toward exoplanets, such as the NASA Kepler mission (Borucki et al., 2010 [1]) and TESS (Ricker et al., 2016 [7]). The motivation behind these efforts of detecting exoplanets lies in the fascination of the human mind to answering the question "Are we alone?" (Howell, 2020 [5]). In this search, benefits can be found whether it is the discovery of a super-Earth or a resource-rich exoplanet that can be mined. In this idealistic search, the hunt for exoplanets has turned into one of the more popular areas for research. Besides the detection research, the categorization study of exoplanets also moves at a fast pace.

Currently, there are mainly five methods for the exoplanet detection: direct imaging, gravitational microlensing, astrometry, radial velocity, and transits. The first method, direct imaging, relies on taking direct photos of exoplanets with reduced glare from the central star. To achieve this outcome, there are two effective techniques. Coronagraphy achieves glare-damped imaging by adding a device inside the telescope to block the light and glare of the star before the photo acquisition. Alternatively, a starshade can be positioned to block light out from a star before it even reaches the telescope. There has been a total of 59 exoplanets detected through the direct imaging method (NASA, 2019 [6]). The second method, gravitational microlensing, relies on the observation of a sudden increase in brightness detected from a distant star. Light coming from a distant star would be bent and refocused at the presence of an exoplanet between the star and Earth (Tsapras, 2018 [10]). Through observing this sudden blip of brightness, there have been a total of 130 exoplanets detected (NASA, 2019 [6]). The third method, astrometry, is extremely difficult to use and as such, there has been only 1 exoplanet discovered through this method (NASA, 2019 [6]). When the exoplanet orbiting around a star is massive enough, it can exert a strong enough gravitational force to make the star wobble around its axis. By looking at the star relative to other nearby stars, the presence of the exoplanet can be detected. However, the wobbling that is present is very subtle leading to this method of astrometry to have limited utility. The fourth method, radial velocity, is similar to astrometry, except that instead of examining the wobble of the star, the light emitted from the star is examined instead. When the star wobbles away from Earth, a redshift would present, and when the star wobbles towards Earth, there would be a blueshift present. Thus, by analyzing the radial velocity, the presence of exoplanets can be determined. There have been 919 exoplanets in total detected through the radial velocity method (NASA, 2019 [6]). The fifth method, transits, is the most popular method, which has discovered 1191 exoplanets (NASA, 2019 [6]). This method relies on tracking the light flux of the star and observing its change in intensity as the transit occurs. When the exoplanet with sufficient size passes directly between its star and the telescope used for measurements, there would be a slight dimming in the light of the star by a measurable amount. The change in light flux is detected by comparing the star to other nearby stars with no such transit which have a relatively constant light flux. As the planet passes directly between the Earth and the star in its system, there would be a sudden dip in brightness as the planet covers some of the light emitted from the star. This process is known as differential photometry, which would have varying results in the perceived dip in brightness depending on the size of the planet and star. This indicates a negative side of the transit method. If the planet is too small or too far away from the star, the dip in brightness would be minimal, rendering the transit method ineffective.

This paper primarily focuses on the detection of exoplanets that orbit stars as rogue exoplanets do not follow a regular pattern of transit in front of a single star. The transit method is used to detect Qatar-1b based on the telescope data collected on July 22nd, 2022. The strengthens and shortcomings of the transit method are further discussed.

2. Data collection

2.1 Tools

In this investigation, data was collected from the Sommers-Bausch Observatory (SBO) (observatory code 463) at the University of Colorado Boulder in Boulder, Colorado, United States of America. The observatory is at a latitude of +40° 00′ 13.36″ N, a longitude of −105° 15′ 467.84″ W, and an altitude of 1653 meters (University of Colorado, n.d. [11]). The observatory's Artemis (East) telescope was used, a CDK20 Optical Tube Assembly PlaneWave Instruments telescope (Figure 1a). The telescope has a 20-inch (0.508 meter) aperture, a 3454mm focal length, a f/6.8 focal ratio, and a 52 x 52 arcminute field (PlaneWave Instruments, n.d. [8]). Images were taken with a SBIG Imaging Systems STF-8300 camera (Figure 1b), which uses a Kodak KAF-8300 CCD. The CCD is 17.96 x 13.52mm with a 3326 x 2504 pixel array, and a total pixel count of 8.3 million. The CCD has a gain of 0.37e−/ADU and a full well capacity of around 25, 500e− (Diffraction Limited/SBIG, n.d. [3]).

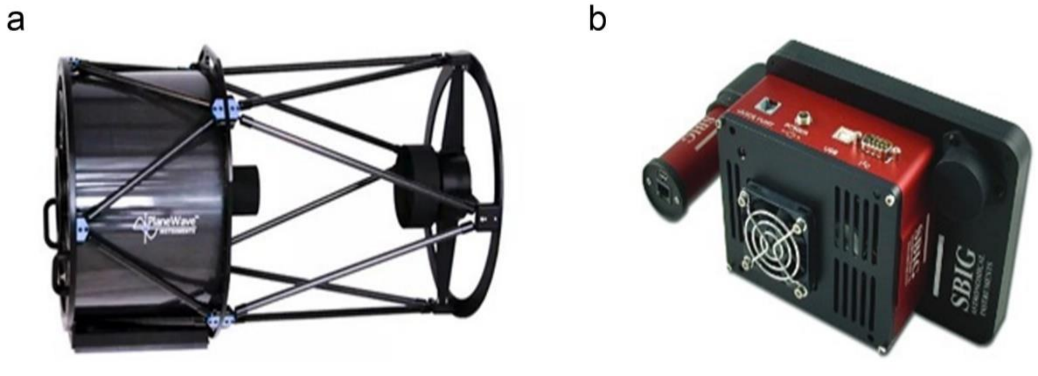


Figure 1. The devices used for data collection. a, CDK20 Optical Tube Assembly PlaneWave Instruments telescope (PlaneWave Instruments, n.d. [8]); b, SBIG Imaging Systems STF-8300 camera (Diffraction Limited/SBIG, n.d. [3]).

While observing, TheSkyX software was used to control the telescope. TheSkyX was also used to slew the telescope to the correct RA and Dec to have Qatar-1 in the star field visible to the telescope. All the frames taken in this investigation were processed by a UV/IR Cut filter.

2.2 Qatar-1b

The exoplanet of Qatar-1 b will be making a transit over its star from 05:00 UTC to 06:39 UTC on July 22nd, 2022. The total predicted duration of the transit is 1 hour 39 minutes. From the Sommers-Bausch Observatory (code 463), the star system will have a right ascension value of 20 hours 13 minutes and 31.65 seconds. The star system will have a declination of +65°09′44.39 arcsec. The star, Qatar-1 has a magnitude of 12.7 and the predicted depth of the transit is 21.4 ppt.

3. Selection of a valid target

To find the ideal exposure time for the transit of Qatar-1 b, calculations can be made relative to the observation data of the asteroid 1994 PC1.

$$\frac{S}{N_{Qatar-1}} = \frac{S}{N_{1994PC1}} \cdot \overline{(2.51)V_{asteroid} - V_{Qatar-1}} \tag{1}$$

Knowing that the magnitude of 1994 PC1 is around 17, the magnitude of the star is 12.7, and the source vs noise of 1994 PC1 is around 25, a value of 150 is obtained for the estimated source vs noise for Qatar-1. This source vs noise is assuming the same exposure time of 40 seconds. Thus

the uncertainty that will be present in the Vmag of Qatar-1 will be 1/150 or around 0.007. Ideally, this uncertainty will be at most, 1 of the change in magnitude of brightness of Qatar-1. This would allow for some certainty in the observation of the transiting planet Qatar-1 b.

To calculate the predicted change in the magnitude of light from Qatar-1, the depth of the transit can be used, knowing that parts per thousand (ppt) in depth = 1.0863 × 10^{-3} mag.

$$21.4\,ppt \times 1.0863 \times \frac{mag}{ppt} = 0.023 mag \tag{2}$$

1/3 of the calculated change in magnitude of Qatar-1 is roughly around 0.007 which is the uncertainty in the magnitude of brightness, calculated in equation 1. As such, it is demonstrated that the transit exoplanet of Qatar-1 b will be able to be detected with an exposure time of 40 seconds.

While the uncertainty in the light curve can be reduced by increasing the exposure period, the over saturation of the CCD chip must be kept in mind.

$$(pixel\ count - dark\ pixel\ count) \times times\ brighter + dark\ pixel\ count = new\ pixel\ count \tag{3}$$

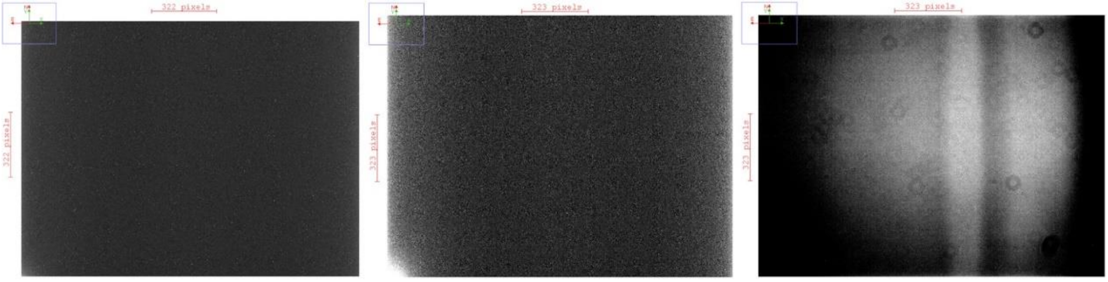
An object of magnitude 12.7 is roughly 36 times brighter than an object of magnitude of 17. In addition, the 1994 PC1 yielded a pixel count of 2800 and had dark frames of 1100 pixel counts. Combining all these numbers, a final pixel count of around 58000 is obtained. As this value is under the saturation point of around 64000, it is possible to use the transit method for Qatar-1 b at an exposure time of 40 seconds. To allow for the difference in light flux to be detected with greater clarity, however, an exposure time of 45 seconds will be used instead. This may be modified at the start of the observation to find a slightly higher exposure time at a point where the star is not saturated, but with a longer exposure time that allows for less uncertainty in the light curve. Alternatively, if the image becomes over-saturated before 45 seconds, an alternative is to combine each set of two images to create more clear changes in magnitude at the cost of more uncertainty in the time aspect of the light flux curve.

4. Observation and image processing

With a start time of 04:28 UTC and an end time of 07:01 UTC, the telescope took a total of 205 raw light frames. There was no smoke, cloud or any other impediments to viewing the sky during the observation of Qatar-1. Throughout the process, there were no sources of the issue in the operation of the telescope. Before taking the series of images, a series of 5 dark frames with an exposure time of 2.5 seconds, 5 dark frames with an exposure time of 45 seconds, and 5 flat frames with an exposure time of 2.5 seconds were taken. For the series of light frames, a total duration of 153 minutes was recorded with the 45 seconds exposure. Each frame taken from the telescope was gathered in the format of FIT files, which can be accessed by AstroImageJ software. Each of the images taken from the telescope shows a similar pattern as the one captured at 04:23 UTC shown in Figure 2. A satellite is present in a few frames of the 205 light frame sequence. However, it did not pass directly through Qatar-1, leaving no impact on the analysis of the exoplanet.

Figure 2. Light frame taken at 04:23:44.585 UTC on July 22nd, 2022

Before analyzing, it is essential to process the light frames to alleviate some interfering factors that shall be accounted for. The image pre-processing procedure includes two main parts: the correction of dark and flat frames and stabilization of the image frames. First, all the light images are to be corrected for dark and flat frames. Dark frames are frames that were taken with the lens cap on the camera. These frames adjust for the random electronic thermal noise from the camera sensor. Flat frames are frames taken of a simple illuminated photo of a blank light score. These frames are used to adjust for the gradients and dust that may be present on the telescope itself. Figure 3 shows images of each frame type taken from the telescope we employed.



45 Second Dark Frame 2.5 Second Dark Frame 2.5 Second Flat Frame

Figure 3. Examples of 3 Types of Frames Taken on July 22nd, 2022

In this investigation, two exposure schemes, 45 and 2.5 seconds, were used for dark frames capture. The selection of the exposure time considers that the flat frames, despite having a short exposure time of 2.5 seconds, still has considerable thermal noise. As such, the short dark frames can be used to correct the flat frames before they are applied to the light frames, which mitigates some errors. To deal with the thermal noise present in the light frames, the dark frames with a longer exposure time were used. In essence, a master frame of the short dark frames will be created. Next, that short dark master frame will be applied to the flat frames. With the corrected flat frames, a master flat frame can be generated. Lastly, a master dark frame, made of the longer exposure time dark frames, can be created. Applying the master flat and master dark frames to raw light frames allows for the adjustment of the light frames.

The second aspect of image processing can now be undergone through stabilizing the light frames. There may be subtle variances in the position of stars due to possible movements in the telescope. To correct for these nuances in positioning, a few target stars can be selected from the image. Then AstroImageJ can stabilize around those selected points. It should be noted that the images had minimal changes after undergoing the image stabilizer process due to the short exposure times.After the two-step image pre-processing, the light flux of the target star, Qatar-1, can be examined and analyzed.

5. Analysis

The light flux of the star can be investigated through aperture photometry. The first procedure is defining the aperture region of the target star and the nearby comparison stars. Through using a few other stars that have a relatively constant light flux, the light flux graph of the interested star, Qatar-1, can be drawn out. On some occasions the acquired data may be unreliable under the effect of some factors such as the clouds over the region of the sky that the telescope is pointed towards. However, in the case of this investigation, it was noted that in qualitative observations there was optimal viewing conditions, indicating that the curve for light flux is fairly reliable.

In this study, an object aperture region of 10 pixels was chosen. Furthermore, the inner and outer radius of the background annulus was chosen to be 15 and 20 pixels, respectively. The object aperture was changed so that it only contained the object of interest. The inner annulus was a dead zone region where the pixels were a transition from the object of interest to the background. As such, this region was not used by AstroImageJ in the calculation towards light flux. However, it was still essential to ensure the accuracy of inner annulus size. The outer annulus was used to measure the background pixel count. It was set as large as possible without infringing onto another star, which would disrupt the background pixel count that is factored into the calculation of light flux. With the target star and reference stars chosen, the graph of the light flux can be determined. At this step, the importance of ensuring the other comparison stars are non-transiting stars should be stressed. While such a case did not occur in this investigation, when generalizing the transit method strategy for exoplanets, it is possible to accidently chose a reference star that also has a transiting exoplanet. As shown in Figure 4, when such a star is chosen, the produced light flux curve of the comparison star will not be relatively constant. This will skew the results for the calculation of light flux for the target star, and as such, a new series of target stars should be chosen.

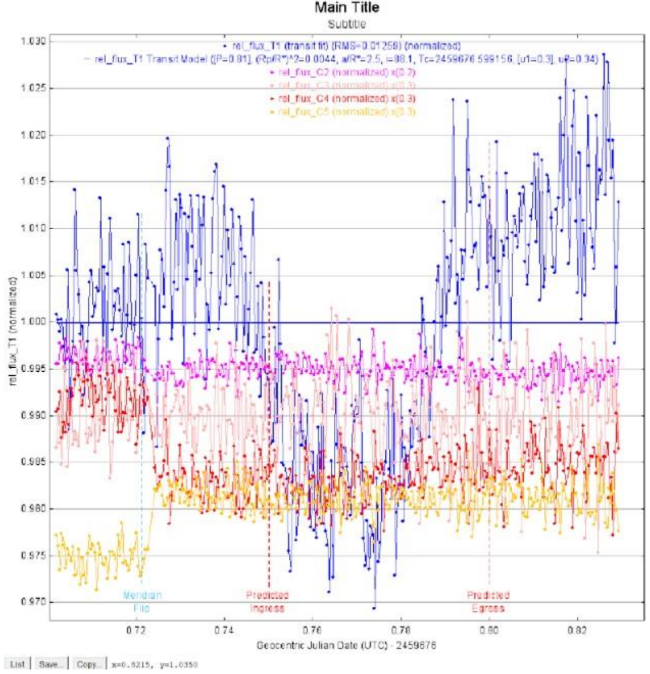


Figure 4. Examples of a Light Flux Curve of a Non-Constant Reference Star

For this investigation, such a scenario did not occur with two constant reference stars chosen. This can be seen in Figure 5(a) where the pink and peach colored lines of the chosen reference stars remain constant throughout the transit of Qatar-1b. As shown in Figure 5(b), there is a noticeable difference in the light flux of Qatar-1 when compared to the chosen reference stars. At this stage, it is clear that there is indeed a transit occurring with a clear dip in brightness illustrating the presence of Qatar-1b. Verification that the exoplanet is indeed Qatar-1b can be seen from adding the predicted ingree and egress of the exoplanet based on previous observational data. As displayed in Figure 5(b), the predicted ingress and exgress match well with that was actually observed leading to the conclusion that it was indeed Qatar-1b that was detected.

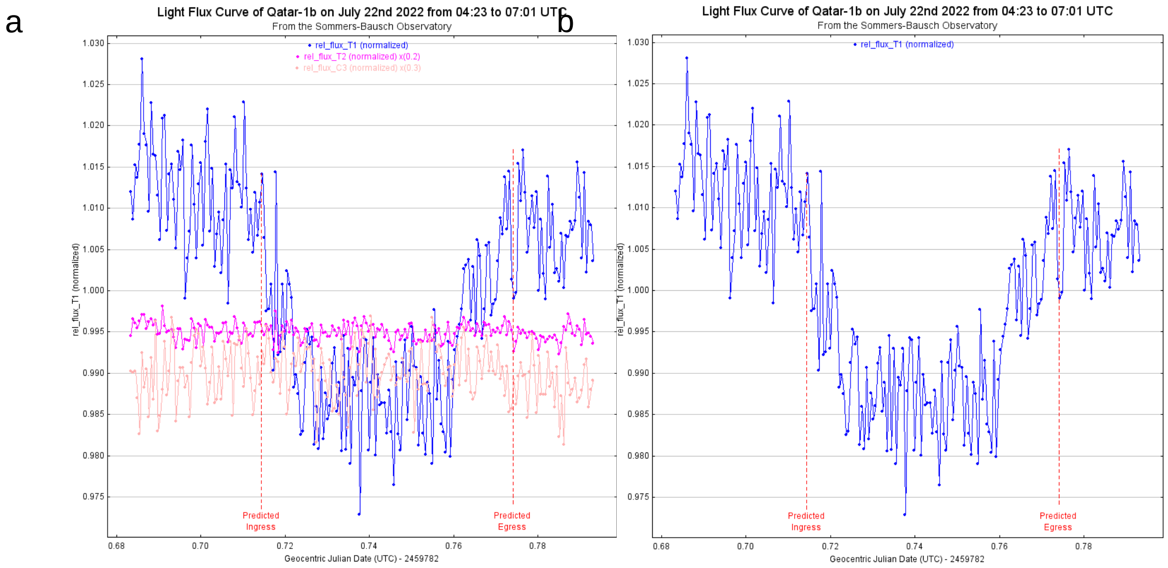


Figure 5. Light Flux Curve of a, Qatar-1 with Reference Stars Shown and b, Qatar-1 without Reference Stars.

6. Discussion and extension

In this section, several strengths and shortcomings of the transit method for exoplanet detection are discussed.

6.1 Strengths of the transit approach

One major advantage of transit approach is that it is excellent at finding exoplanets in a close orbit to the central star. Benefited from this feature, the transit method can detect a much more distant exoplanet than other methods as long as it is close to the central star. This merit of transit method allows space telescope such as Hubble to detect a large quantity of exoplanets.

Another benefit of transit method is that it allows good extension. This investigation focused on the determination of whether or not, the data gathered can be extended into further calculations of the properties of the exoplanet, Qatar-1b. For instance, from the curve of the light flux, the period of orbit of the exoplanet can be determined. This works through using the known size of the central star and studying how much the light dips when the exoplanet passes in from of the star. In addition, the diameter of the exoplanet, a quantity that could not be measured otherwises, can be found through using the transit method in reference to the radial-velocity method. If the planet that is in transit possesses an atmosphere, some wavelengths of light emitted from the star would be blocked by the exoplanet on its way to Earth. Through using the spectrum of light coming from a star and exoplanet system during the transit and outside of a transit, the dips within the spectrum of light can be used to find the composition of the exoplanet. This process leads towards the categorization of exoplanets, allowing for the hunt towards resource rich or super-Earth exoplanets to become a reality. Perhaps the most eminent benefit of the transit method, however, is how it can be operated on a massive scale. Telescopes can observe a massive amount of space at same time, easily watching 100 000 stars at once (Staff Writers, 2002 [9]). This simultaneous observation of stars allowing for the field of exoplanet detection to carry forward at a rapid pace.

6.2. Shortcomings of the Transit Approach

One of the biggest shortcomings of the transit approach is that it fails to detect planets that have a longer orbital period or planets that are further away from the star it orbits around. Most of the planets detected through the transit method tend to be hot Jupiters that orbit very close to their star with a very short period or orbit (Staff Writers, 2002 [9]). The transit method relies on observing many iterations. a transit to be sure that there is actually an exoplanet present. However, for exoplanets with longer orbits, such a task is much more difficult. In addition, for a planet that is further away from its star, or for a dimmer star, the change in light flux is simply too small to be detected by the current telescopes. In this regard, there is a very bias in the transit method in the detection of exoplanets that are hot Jupiters - large with a small orbit.

Another shortcoming of the transit approach is that the exoplanet must pass directly between the star it orbits around and Earth. Without this condition, the detection of an exoplanet can’t take place as there would be no change in the light flux detected. However, this condition is not universally true. In fact, for most exoplanets, the orbital plane will not fit, edge-on with Earth-based observers. With these exoplanets and rogue exoplanets that do not orbit a star, there is a vast quantity of exoplanets that cannot be detected through the transit approach.

Finally, the transit approach will sometimes yield false positives as large exoplanets can be mixed up with small stars. With similar sizes, when these celestial objects pass around a large star, the light flux curve attained will be similar. However, the shortcoming is somewhat mitigated through the need for many observations of an exoplanet, attaining many of its properties, before it is confirmed.

7. Conclusion

Qatar-1b is one of two confirmed exoplanets orbiting Qatar-1. Qatar-1 is a hot Jupiter with a short orbit as seen from the short transit time. Further research into the planet can produce the exact predictions of the radius and other similar properties relating to the planet. This paper, however, has highlighted how in such a process of transit, an exoplanet can be investigated. Further extensions of the transit method can be targeted toward systems with more than one transiting exoplanet. As the situations get more complex, it can be investigated how the light flux curve of the transit method will be changed as multiple objects interact.

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