Exoplanet Transits: Light Curve Photometry

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***Abstract*—Over the course of several weeks in July 2012, three separate exoplanet transits were observed and corresponding flatfield and dark images were taken for each run for image processing. Photometry was applied to processed images to create light curves for each transit from which information about magnitude and times of interest during each transit could be estimated. This information was used to calculate properties of each exoplanet and their orbits which were then compared to accepted values. Observations and analysis were successful.**

I. Introduction

THE study of exoplanets is a new and active field in astrophysics that involves observations of planets orbiting stars other than our Sun. This statistical study of planetary systems is important because it provides us with information on how planets form and evolve, and can confirm or deny the uniqueness of our own solar system.[1] There are many methods in use for the detection of exoplanets and new methods are currently being developed. The two most reliable methods for exoplanet detection are the radial velocity and transit methods. The radial velocity method involves study the Doppler shift of the incoming light from a host star and looking for discrepancies possibly caused by the presence of an exoplanet.[2] If an exoplanet passes in front of its host star while in the plane of view of our solar system it creates a transit that is viewable from Earth. This more easily observed method involves studying the variation in the light curve of a host star during a transit to gain information about its exoplanet.[3] New methods such as direct imaging, previously thought to be impossible, are being developed by organizations like NASA to further advance the study of exoplanets.[4]

During the summer of 2012 the transits of three different exoplanets were observed at the Paul and Jane Meyer Observatory in order to test the image processing program Astro ImageJ in its ability to analyze observations of objects with varying light curves. An algorithm was created for the processing of information received from these transits and light curves for each transit were produced. From these curves, information about the ingress, egress, and magnitude drop of each transit were obtained, and the radius, semi-major axis, and velocity of each planet were calculated. From this process it was determined that the method applied to analyzing these transits was reliable, and that these were the first successful exoplanet transit observations to be performed at the Paul and Jane Meyer Observatory.

II. Theory

The radius of an exoplanet can be calculated using information obtained from its transit. The drop in magnitude during a transit is proportional to the ratio of the size of a host star and its exoplanet. As the planet passes in front of the star it blocks a portion of light corresponding to its surface area. Therefore the ratio of the star's light to the blocked light is equal to the ratio of the surface area of the star to the surface area of the planet. This is expressed in Equation 1.

$$\frac{I_0 - I_T}{I_0} = \frac{\pi R_B^2}{\pi R_A^2} = \left(\frac{R_B}{R_A}\right)^2$$

$$A - Star \quad B - Planet$$

(1)

If the drop in magnitude and the radius of the host star are known, it is possible to calculate the radius of the exoplanet from this relationship.

Through multiple observations of the same transit, the period of orbit of an exoplanet can be obtained. Using this information and Kepler's third law it is possible to calculate the semi-major axis of the orbit of the exoplanet . Kepler's third law is stated in Equation 2.

$$P_B^2 = \frac{4\pi^2 a_B^3}{G(M_A + M_B)}$$

(2)

In most situations, the mass of the exoplanet is negligible when compared to the mass of the host star and can be disregarded in Kepler's third law. To prove this, the equation for mass from density can be utilized. This is given in Equation 3.

$$\frac{M_B}{M_A} = \frac{\rho_B (4/3)\pi R_B^3}{\rho_A (4/3)\pi R_A^3}$$

(3)

After the radii for the host star and exoplanet are obtained, a ratio for the density of the host star and exoplanet is estimated based on the densities of materials relevant to planets. (Stars have densities nearly equal to that of water while planets are expected to be at most 10 times the density of water.) The volume term is small enough (on the order of 1/1000), the mass of the exoplanet is negligible and can be disregarded from Kepler's third law, leaving the remaining variable to be the semi-major axis of the planet's orbit.

$$a_B = \left(\frac{G M_A P_B^2}{4\pi^2}\right)^{1/3}$$

(4)

Once the semi-major axis is obtained, the velocity of the planet in its orbit can easily be calculated using Equation 5.

$$v_B = \frac{2\pi a_B}{P_B}$$

(5)

III. Observations

The transits of three separate exoplanets were observed at the Paul and Jane Meyer Observatory over the course of several weeks in July 2012. Objects were carefully chosen by a certain set of criterion before observations were made. The NASA Exoplanet Archive's Viewable Transit Service provided a list of possible transits to be viewed from a latitude of 31° N and longitude of 97° W.[5] NASA's archive also provided data on each transit that was vital for determining whether they could be observed through the 26 in. telescope at PJMO.

For a specific transit, the right ascension and declination of the host star were given and these determined whether the transit would be in the correction position in the sky to be seen. The transit duration and Universal Time were also provided and these determined whether the transit would occur at the right time to be observed at PJMO, and if there was enough time in the night to capture the entire transit. The exoplanet's size was given and large planets such as 1.5 times the size of Jupiter were preferred because they provided a larger drop in magnitude during the transit.

The estimated drop in magnitude, or transit signature, was the most important piece of information provided by the archive because it determined how exposures were set up and whether the transit could be detected by the instruments being used. A 2% drop in the signal, or total number of counts due to the transit, was preferable for the transit signature, where the signature was three times the noise. Counts are the number of individual photons collected on each CCD pixel during an exposure and noise is the error of the readout of those counts. For these preferences, the minimum number of counts necessary for the transit signature to be distinguished from the noise in this way, needed to be determined. The signal is proportional to the number of counts and in counting statistics noise is proportional to the square root of the number of counts. Therefore the signal over the noise is proportional to the square root of the number of counts. This is shown below.

$$S \propto C$$

$$N \propto \sqrt{C}$$

$$\frac{S}{N} \propto \sqrt{C}$$

(6)

So depending on the desired difference between the transit signature and noise, the signature determines the noise which can be used in this relationship to find the minimum necessary number of counts. Then, depending on how many counts are collected per second on each pixel in the CCD, the length of individual exposures can be determined. Exposures should be long enough to capture well over the minimum number of counts, but not so long that pixels become saturated. For the CCD camera at PJMO, each pixel becomes saturated at around 65,500 counts. 30 sec exposures were used for all transit observations at PJMO. NASA’s archive also provided information on the estimated ingress and egress times, the beginning and end of the transit, which allowed for planning the runtime of each observation. It is usually preferable to begin exposing an hour before ingress and continue exposing an hour after egress.

IV. METHOD

Once observations were completed image processing and analysis could begin. An algorithm was written for the image processing program Astro ImageJ to be executed following transit observations. To begin the process, flatfield and dark images needed to be taken. Flatfields were taken with the telescope pointed at a completely uniform, white surface for the same exposure time as target images (30 sec). These images reveal interference such as dust or other things that may cause variation in response across the CCD that need to be reduced from target images. Darks were taken with the telescope covered for a zero second exposure. These images show variation among pixels in the CCD that is caused by the thermal noise and electric interference of the camera and CCD themselves. These must also be reduced from target images. Ten of each of these types of images were taken for image processing.

Once the flatfields and darks were obtained, Astro ImageJ was used to reduce them from the target images taken of each transit. First the flatfields had to be normalized. This involved averaging all ten flatfields together to create a single image. Then the average pixel value over that single image was taken and the image was divided by this number to create a final, master flatfield image. This process allows the counts of each pixel to average out to a more comprehensible number, usually from zero to one where one is brightest, instead of displaying the large number of counts originally collected. Performing normalization can help the resolution of images and provide a better sense of what is happening with the counts on each pixel. For the darks, all ten images needed only to be averaged together to create one master dark image. Then the two master images were reduced from the target images. This was done by first subtracting the master dark from all target images and then dividing the target images by the master flatfield.

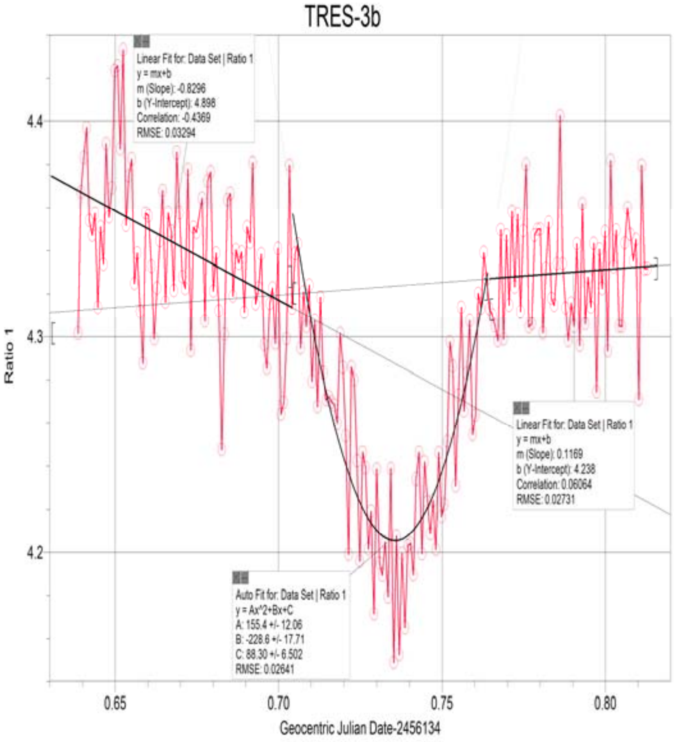
The target images were then ready to be analyzed to create light curves with information about each transit. To do this, the photometry tool in ImageJ was used and the aperture was set to automatically capture and subtract the sky-count from target objects. The target star and one or more comparator stars were chosen with the photometry tool which collected information on the counts of each object at different times. Astro ImageJ provides options for creating light curves from this information. To obtain the most useful curve the x-axis was set to the Geocentric Julian Date of each exposure and the y-axis was set to the ratio of the target star to the sum of all comparator stars. The resulting light curve was then used to find the information necessary to make the calculations described in the theory section above. By fitting several curves to the data in the light curve, this information was found.

First, the durations of the ingress and egress were identified on the light curve. These are the periods of time in which the exoplanet is not entirely within or out of the view of the host star, at the beginning (ingress) and end (egress) of the transit. On the light curve, these times are represented by the length of the negative and positive slopes that occur during the first and second magnitude shifts, respectively. The nearly flat section between these slopes is the transit of totality in which the surface of the exoplanet is completely within the surface of the view of the star. The nearly flat sections on either side of these slopes are the times in which the surface of the exoplanet is completely outside the view of the host star. The time from which ingress starts to the end of egress constitutes the entirely of the transit and the minimum magnitude during this time was found by fitting it to a quadratic curve using the graphing program LoggerPro. The maximum magnitude was then found by fitting both flat durations before and after the transit to a linear curve in the program. These values give the total magnitude difference throughout the transit which can be used to calculate the radius, semi-major axis, and velocity of the exoplanet as explained in methods.

V. RESULTS

The three transits observed at PJMO where CoRoT-2b, CoRoT-11b, and TRES-3b. Complications were experienced with CoRoT-11b and the first run of CoRoT-2b. TRES-3b and the second run of CoRoT-2b produced the only useful data and analyzable light curves.

Figure 1 shows the run of TRES-3b taken on July 25th and the curves used to fit its data.



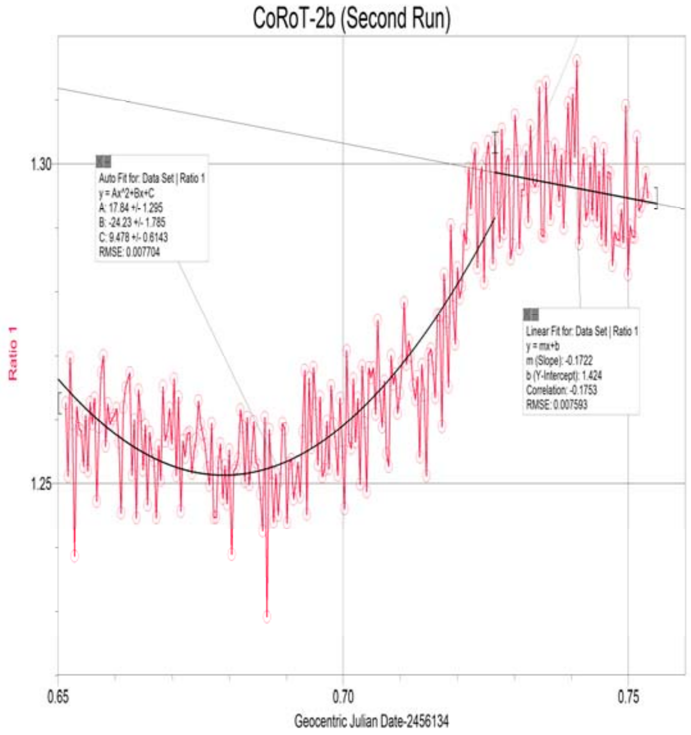
For planet b of the TRES-3 solar system the following information in Table 1 was calculated.

Radius (R_J)	Volume Term	Semi-Major Axis (AU)	Velocity (km/s)
1.28	0.00428	2.28×10^{-2}	190

Table 2 gives the accepted values for comparison.

Radius (R_J)	Semi-Major Axis (AU)
1.305	2.26×10^{-2}

Figure 2 shows the second run of CoRoT-2b taken on July 19th and the curves used to fit its data.



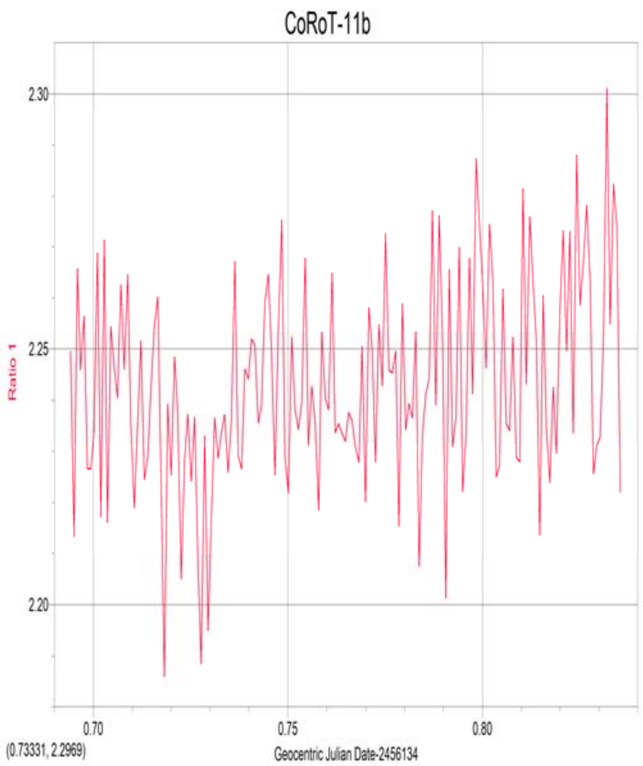
For planet b of the TRES-3 solar system the following information in Table 3 was calculated.

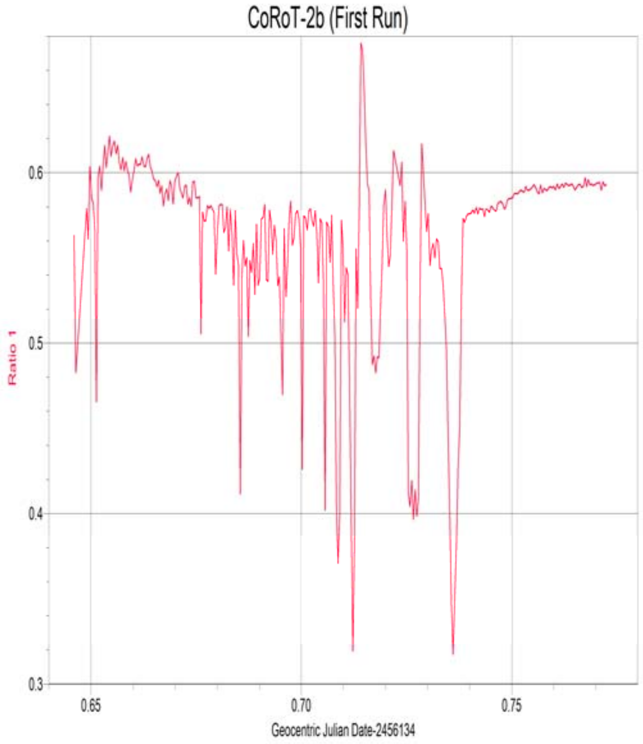
Radius (R_J)	Volume Term	Semi-Major Axis (AU)	Velocity (km/s)
1.41	0.00267	2.87×10^{-2}	179

Table 4 gives the accepted values for comparison.

Radius (R_J)	Semi-Major Axis (AU)
1.46	2.81×10^{-2}

Figures 3 and 4 show the unusable runs of CoRot-11b and CoRoT-2b respectively, taken on July 24th and July 12th respectively.





The run of CoRoT-11b was unsuccessful due to false information found on transit duration. The entire transit could not be captured. The first run of CoRoT-2b was unsuccessful due to condensation on camera lens, most likely caused by high humidity, interfering with exposures. No filter was used for this run. If a filter had been used to cover the lens, condensation could have been avoided.

VI. Discussion

The calculated results given above are within the error of the accepted values given for each exoplanet. This suggests that the method applied at PJMO for observing and analyzing exoplanet transits is reliable and that the three exoplanets observed in July 2012 were the first successful attempts at PJMO. The complications experiences during some of these observing sessions should be kept in mind for future work in this area. Future observations need not be limited to exoplanet transits. The image processing and light curve analysis of the method provided can be applied to any object with a varying light curve such as variable stars and moons or other objects like Hyperion, a moon of Saturn, that display irregular shifts in magnitude over time. (Some variable stars were in fact observed in the star field of CoRoT-11b during its run.)

VII. Conclusion

Over a period of several weeks, three different exoplanet transits were observed at the Paul and Jane Meyer Observatory. Exposures were taken over the duration of each transit and flatfield and dark images were made for each observation run. Target images were processed using an algorithm for the image processing program Astro ImageJ and photometry was used to create light curves in the program for each transit. Sections of each light curve were analyzed using linear and quadratic fits in the graphing program LoggerPro and information about ingress, egress, and magnitude drop were obtained. This information was used to calculate the radius, semi-major axis, and velocity for each exoplanet observed. These results were compared to accepted values and the method of observation and analysis at PJMO was found to be reliable. Future work using this method can be applied to other objects with varying light curves.

VIII. Acknowledgment

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