Light Curve Analysis for Transit of Exoplanet Qatar-1b

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***Abstract*— The study of exoplanets offers a glimpse into the composition of our universe. Although much interest lies in finding Earth-like exoplanets, hot Jupiters are easier to find and provide insight into other solar systems. We observed the hot Jupiter, Qatar-1b, using differential photometry to generate a light curve of the transit. Physical characteristics of the exoplanet were found by fitting a limb-darkened, light curve equation to the collected data. Normalized to Qatar-1, the planet radius was 0.145, the impact parameter was 0.68, and transit time was 5,690 seconds. From those parameters, the stellar density was found to be 2371.33 kg/m^3 and orbital inclination angle at 83.49°.**

I. Introduction

EXOPLANETS are planets that orbit a star outside of our solar system. The first exoplanet was detected in 1992 and the first exoplanet was confirmed in 1995. Since then, over a thousand have been detected and confirmed. Even the closest ones are many light-years away, so simply looking through a telescope will not reveal an exoplanet.

The main methods for detecting exoplanets include transit photometry and the radial-velocity (or Doppler spectroscopy) method. The radial-velocity method analyzes spectra from a target star and measures the change in relative velocity of the star as it moves around its center of mass, due to the gravity of a nearby planet [5]. However, the method used in this paper was differential photometry.

When a planet passes in front of its star when viewed from Earth, the brightness of the star slightly drops. The amount that the star dims is related to the size of the star and planet; the larger the planet, the more the star will appear to dim. Photometry measures the change in the amount of light that comes from a target star over time (flux) during a planet's transit. Differential photometry measures the change in flux of a target star relative to nearby comparator stars. When a planet transit occurs, the flux of the target star decreases, while the fluxes of the comparator stars remain constant. Creating a light curve of flux versus time of a planet transit with comparator stars will show a definite drop in flux of the target star. Differential photometry differs from absolute photometry since the latter does not take comparator stars into account and can be affected by weather conditions, changing air mass, etc.

The main objective in looking for exoplanets is to find Earth-like planets capable of sustaining life. Planets within the habitable zone, usually up to a few astronomical units away from their star, are particularly interesting to observers because of the possibility that they are home to liquid water, and even life. Hot Jupiters are easier to detect than smaller, rocky planets because they block more light from their star as they transit. Also, hot Jupiters orbit closer to their host star, so they have many more possible observable transits [5]. Although these planets are not what astronomers are primarily trying to find, they still give insight to other solar systems.

Several factors must be taken into consideration when finding observable exoplanet transit times. The transit must occur within the astronomical twilight period, so that the sun's light does not interfere with the data. Also, since data is taken before and after the transit itself, the transit must begin at least about an hour after the start of astronomical twilight and end at least hour before the end of astronomical twilight. Apparent magnitude (vmag) is a measure of the brightness of an object observed from Earth. An ideal vmag for a target star would fall in the range of ten to 14, so that it is bright enough to observe a transit, yet not too bright to saturate the photon counts in the images. The transit depth (mmag) is the change in observed flux due to a planet's transit across its star, and corresponds to the depth of the light curve. An ideal mmag for a transit would be greater than ten, meaning a 1% change in flux.

The right ascension and declination of the target star must be taken into consideration as well to make sure that the transit does not occur when it is close to the horizon. When viewing objects close to the horizon, there is more atmospheric disturbance that will affect the images, so having the target star higher in the sky (near zenith) is more favorable. Also, the brightness of the moon must be considered when choosing observation nights. The moon gives off too much light when it is full or close to being full, so observations are not possible for several nights each month. Finally, the weather plays an important factor in being able to carry out observations because the presence of clouds makes it impossible to take meaningful data. The Swarthmore College database and the Czech Astronomical Society database were the two sources used for gathering information on transit times for this project.

II. Method

A. Physical Observation

Observations were taken in the summer of 2015 at the Paul and Jane Meyer Observatory in Clifton, Texas of the Central Astronomical Society. The transit of Qatar-1b was observed on the night of June 25, 2015. The telescope is a 0.6m Ritchey-Chretien reflecting telescope with a CCD (charge-coupled device) chip in the camera. A Princeton Instruments ProEM-HS: 1024 BX3 camera was used. The CCD chip collects and counts photons of light from objects in the sky that the telescope is pointed at. The CCD chip is cooled down to -60°C to reduce thermal noise that would otherwise negatively affect the data. Nitrogen is passed through the chip so that ice crystals do not form on the chip, which would also affect data.

Calibration frames are the first images taken and consist of bias, dark, and flat frames. Bias frames are used to subtract noise from the CCD chip. 30 sets of bias frames were taken at a zero-second exposure time. Dark frames are used to subtract thermal noise from the camera due to electrical current. 30 sets of darks at ten-second exposure and 30 sets of darks at 30-second exposure were taken. The bias and dark frames were taken with a blocking filter so that the internal noise could be subtracted. Flat frames are used to subtract imperfections on the telescope lens and mirror, such as dust particles. 30 sets of flats were taken at a ten-second exposure time. The flat frames were taken with a BG40 filter.

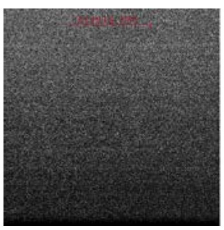

Fig. 1a. Bias

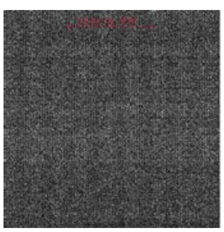

Fig. 1b. Dark30

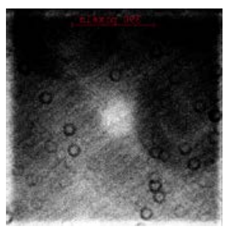

Fig. 1c. Flat10

Fig. 1a. A bias frame with zero exposure. Fig. 1b. A dark frame with 30-second exposure. Fig. 1c. A flat frame with ten-second exposure.

After the calibration frames were taken, a star finder chart was used to locate target star Qatar-1 and point the telescope at it. Next, the telescope focus was adjusted so that the full width at half maximum of the photon counts for the star was as low as possible. Finally, the actual observation was started and the light images were taken with a BG40 filter at a 30-second exposure time. Qatar-1's values for vmag (12.84), mmag (20.4), and right ascension/declination were all favorable for observing the transit. Also, there was no full moon or clouds, and the transit occurred during astronomical twilight.

B. Image Processing and Creating Light Curve

The AstroImageJ 3.1 software was used to process the images gathered from the telescope and create a light curve. First the master calibration files were created from the bias, dark, and flat frames. The dark frames at ten-second exposure were used to create the master flat image and the dark frames at 30-second exposure were subtracted from the light images. Next, the images were aligned and stacked. Then, three comparator stars were chosen. They were chosen because they were bright stars nearby Qatar-1, but not too bright to saturate the photon counts. Finally, the light curve was generated and the data from the target star was exported so that a mathematical model could be fit to it. Fig. 3 shows the light curves for the star Qatar-1, the comparator stars, background, and airmass.

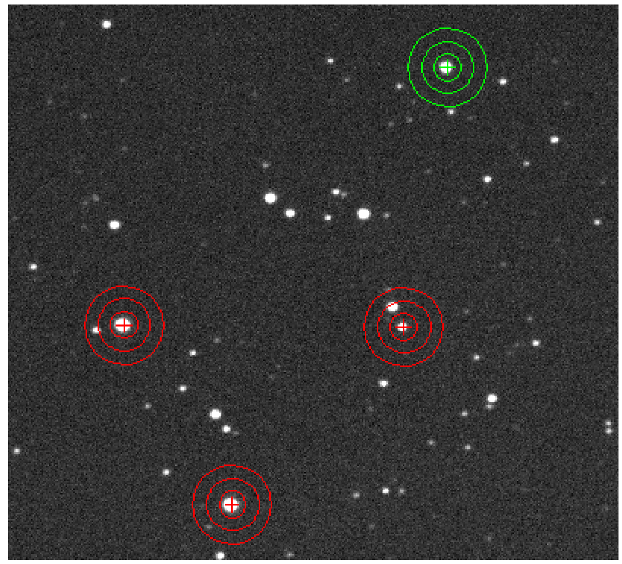

Fig. 2. Qatar-1 is show in the green aperture and the three chosen comparator stars are in the red apertures.

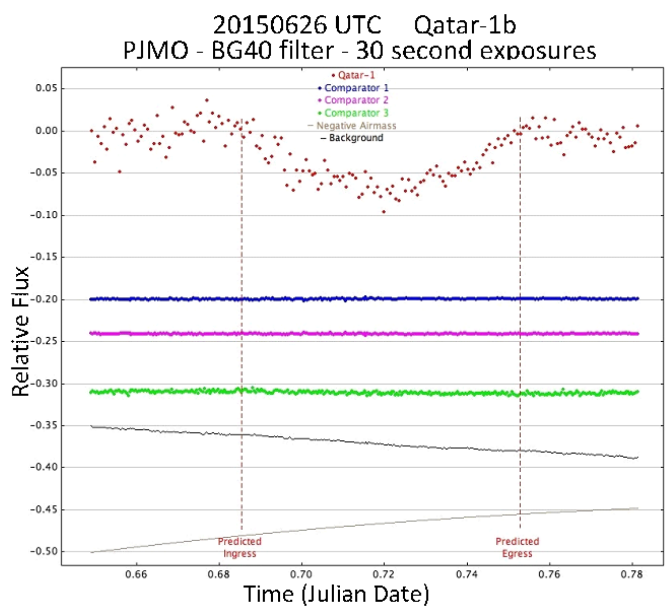

Fig. 3. The light curve created in AstroImageJ using differential photometry. Qatar-1's curve is at the top in red, the three comparator stars are in blue, pink, and green, background is in black, and negative airmass is in brown at the bottom.

C. Model Fitting

The exported data was fit to a mathematical model of a light curve described in the paper by K. Mandel and E. Agol in 2002 [1]. The first model assumes uniform star brightness.

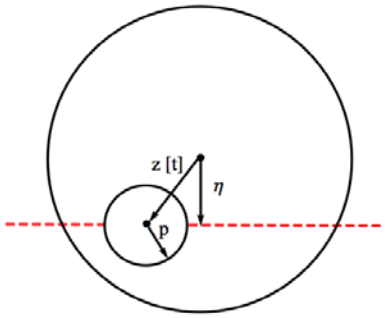

Fig. 4. A diagram showing *z[t]* (center-to-center distance), *p* (normalized radius of the planet), and η (impact parameter). The dotted red line shows the path of the transiting planet.

The distance from the center of the star to the center of the transiting planet is *z[t]*. The normalized radius of the planet, *p*, is the radius of the planet divided by the radius of the star is. The impact parameter η is the vertical distance between the center of the star and the transit path, normalized to the radius of the star.

$$z[t] = \sqrt{v^2(t - t_m)^2 + \eta^2} \quad (1)$$

In (1), v is the velocity of the planet, t is time, and t_m is coordinate time when the planet is at the middle of the transit. The flux of the light curve can be expressed as the following piece-wise equation:

$$\text{Flux}(t) = \begin{cases} 1, & z[t] > 1 + p \\ F[t], & |1 - p| < z[t] \leq 1 + p \\ 1 - p^2, & z[t] \leq 1 - p \end{cases} \quad (2)$$

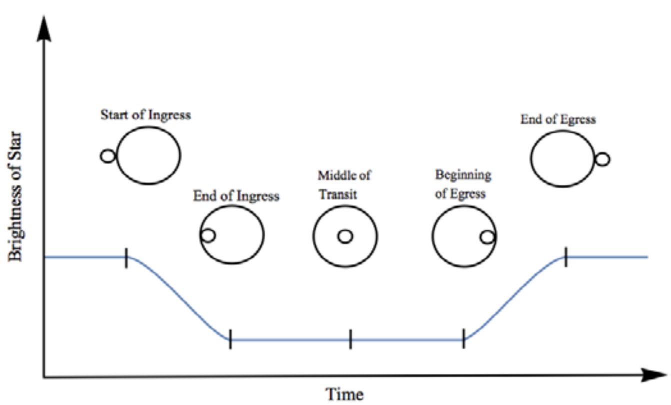

Fig. 5. Diagram of a light curve with the positions of the star and planet at different times during the transit.

In the first case of (2), the flux is one since the planet is not blocking the star; it corresponds to the time before the transit and after the transit. The second case is during the planet's ingress and egress, and correspond to the diagonal portions in Fig. 5. The third case is when the planet appears to be fully inside the disc of the star, and corresponds to the bottom of the light curve in Fig. 5.

$$F[t] = 1 - \frac{1}{\pi}\left[p^2\kappa_0[t] + \kappa_1[t] - \sqrt{\frac{4z[t]^2 - (1 + z[t]^2 - p^2)^2}{4}}\right] \quad (3)$$

During ingress and egress, the flux is described by (3).

$$\kappa_0 = \cos^{-1}\left[\frac{(p^2 + z^2 - 1)}{2pz}\right] \quad (4)$$

$$\kappa_1 = \cos^{-1}\left[\frac{(1 - p^2 + z^2)}{2z}\right] \quad (5)$$

Equations (4) and (5) relate to the area of the secant when the planet is going across the viewable disc of the star.

$$t_b = t_m - \frac{dt}{2} \quad (6)$$

Equation (6) is the time that data was taken before the ingress. The variable *dt* is the duration of the transit.

$$v = \frac{2\sqrt{(1 + p)^2 - \eta^2}}{dt} \quad (7)$$

Equation (7) describes the velocity of the planet. The equations were put into Wolfram Mathematica and the parameters *p*, η, *dt*, and t_m were manipulated to fit the data. A variance equation was used to create a least-squares fit to the data. Also, a polynomial was added to the flux function to compensate for the change of airmass throughout the observation night. The following model was created from this method:

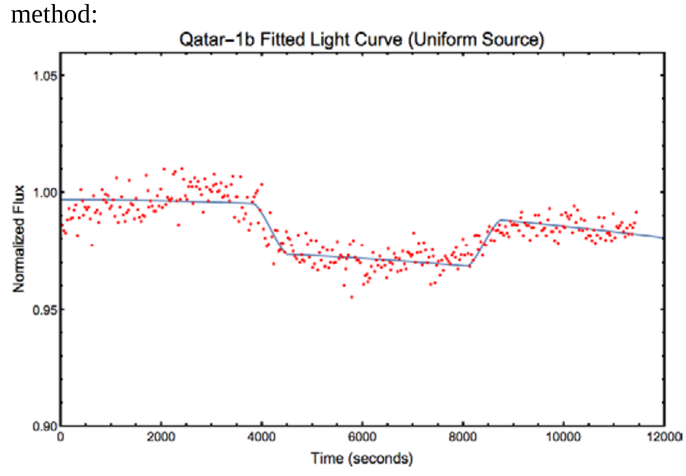

Fig. 6. Fitted model plotted with the data from the transit of Qatar-1b, assuming uniform star brightness.

After creating a fit assuming uniform star brightness, a limb darkening model was created. Limb darkening describes the phenomenon where stars appear brightest near the center, where the star has a higher temperature, and dimmer toward the edges, where the star has a lower temperature. The limb darkening model is for small planets, or planets with a normalized radius of around 0.1.

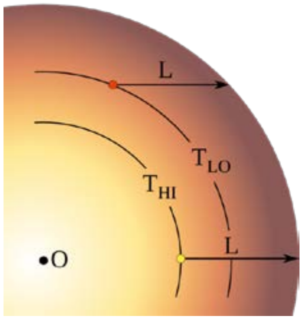

Fig. 7. Limb darkening diagram showing temperature and brightness differences [6].

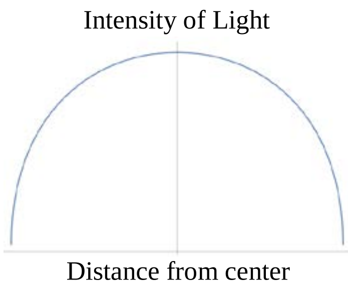

Fig. 8. Graph illustrating that as distance from the center of the star increases, intensity decreases.

$$I[r] = 1 - \gamma_1(1-\mu) - \gamma_2(1-\mu)^2 \tag{8}$$

$$\mu = \sqrt{1-r^2} \tag{9}$$

Equation (8) is the specific intensity, where μ depends on the radius and is defined in (9). The main flux equation for the light curve for small planet limb darkening can be expressed by the following equation:

$$\text{Flux}(t) = \begin{cases} 1, & z[t] > 1+p \\ F_1[t,p], & 1-p < z[t] < 1+p \\ F_2[t,p], & z[t] \leq 1-p \end{cases} \tag{10}$$

Once again, the first case corresponds to before and after the transit, the second case is during ingress and egress, and the third case is for when the planet is fully inside the disc of the star.

$$F_1[t,p] = 1 - \frac{L[t,p]}{4\pi\Omega}\left(p^2\cos^{-1}\left[\frac{z[t]-1}{p}\right] - (z[t]-1)\sqrt{p^2-(z[t]-1)^2}\right) \tag{11}$$

$$F_2[t,p] = 1 - \frac{p^2 L_2[t,p]}{4\Omega} \tag{12}$$

These equations are from the second and third cases, respectively, in (10). These two equations are made up of the following equations:

$$L[t,p] = (1-a)^{-1}\int_{z[t]-p}^{1} I[r]\, 2r\, dr \tag{13}$$

$$L_2[t,p] = \left(4\, z[t]p\right)^{-1}\int_{z[t]-p}^{z[t]+p} I[r]\, 2r\, dr \tag{14}$$

$$\Omega = \frac{1}{4} - \frac{\gamma_2}{24} - \frac{\gamma_1}{12} \tag{15}$$

$$a = (z[t]-p)^2 \tag{16}$$

The constants $\gamma_1 = 0.595$ and $\gamma_2 = 0.1155$ depend on the characteristics of the star Qatar-1 [4]. The equations were put into Mathematica and the parameters p, η, dt, and t_m were manipulated to fit the data. The variance equation was used once again to create a least-squares fit to the data. The model created from this method is shown in Fig. 9.

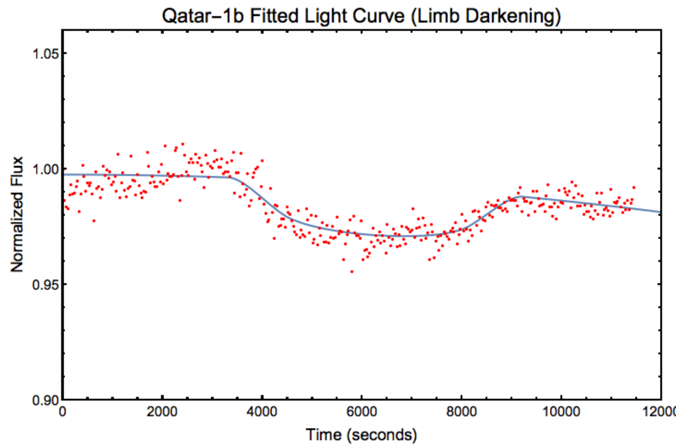

Fig. 9. Fitted model plotted with the data from the transit of Qatar-1b, taking small planet limb darkening into account.

III. Results

Table I lists the values from the parameters that were varied to achieve best-fit curves.

TABLE I
Values for Parameters

Parameter	Calculated Value (Uniform Source)	Calculated Value (Limb Darkening)	Published Value
p	0.145	0.145	0.1455 $\pm$ 0.0015
dt	5200 seconds	5690 seconds	5802 $\pm$ 1.382 seconds
η	0.67	0.68	0.696 $\pm$ 0.024
ρ_s	3106.84 kg/m^3	2371.33 kg/m^3	2143.2 $\pm$ 169.2 kg/m^3

Table I shows parameter values calculated from the uniform source model and limb-darkened model, along with published values [3].

The density of the star, ρ_s, was obtained by using Kepler's third law, assuming a circular orbit, and using a published value for the period of the orbit of the planet. Table II lists values of parameters that were calculated from previously fitted parameters from the limb-darkened model and published values.

TABLE II
Values for Calculated Parameters

Parameter	Calculated Value	Published Value
R_p	1.189 $R_{Jupiter}$	1.164 $\pm$ 0.045 $R_{Jupiter}$
i	83.49°	83.47° $\pm$ 0.38°

Table II shows parameter values calculated from the limb-darkened model, along with published values [3].

The parameter R_p is the radius of Qatar-1b in terms of the radius of Jupiter. The orbital inclination angle, *i*, is the angle of the plane at which Qatar-1b orbits its star. It is calculated from the following equation:

$$i = \cos^{-1}\left[\frac{\eta}{a}\right] \quad (17)$$

IV. Discussion

Based on the characteristics of Qatar-1b, we can distinguish the planet as a hot Jupiter, meaning it is a large planet orbiting close to its star. To put it in perspective, the normalized radius of this exoplanet is around 0.145, whereas the normalized radius of Jupiter is 0.100. This means that Qatar-1b is larger in relation to its star than Jupiter is in relation to the sun. Also, Qatar-1b is larger than Jupiter, since its radius was found to be greater than that of Jupiter.

Comparing Fig. 6 and Fig. 9, it is clear that limb darkening improved the model fit to the transit data. This is supported by values from the least-squares variance function, which is lower for the limb-darkened value than the uniform source model. A change that could have been made was to make a model from the airmass data itself and use it with the equations for flux to compensate for the changing airmass. A simple, general polynomial function was used in the Mathematica code to create the models, so implementing this change may have given better results. Also, having more observation nights of the transit of Qatar-1b would give more precise results.

The calculated values for *p* for both models are consistent with the published value. This is most likely because *p* simply depends on the change in flux due to the transit, and this did not change between the two models. Both of the calculated values for *dt* were off from the published value. A possible reason for this is that the transit distance of the planet was assumed to be two-dimensional. However, in reality, the planet travels an arc length distance, which is slightly larger than the assumed straight path.

V. Acknowledgment

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