# Observation and Analysis of exoplanet, Qatar-1b

Dana Cody, Dhiraj Bansal, Chloe Herrera

***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. Two sets physical characteristics of the exoplanet were found by fitting a light curve equation to the collected data. A limb darkening analysis gave normalized a planet radius of 0.145, an impact parameter of 0.68, and a transit duration of 5690 seconds. A uniform analysis gave a normalized planet radius of 0.145, an impact parameter of 0.67, and a transit duration of 5200 seconds. From there we calculated values for physical characteristics such as density of the star, orbital inclination, and planet radius.**

***Index Terms*—differential photometry, exoplanets, hot Jupiter, light curve, limb darkening, Qatar-1b**

## I. Introduction

MORE than three hundred and forty planets have been discovered outside of our solar system. This is pretty impressive considering the first exoplanets were discovered in 1995. The majority of exoplanets have been discovered using Doppler spectroscopy, which is observing the shift in the wavelength of the starlight, due to the planets gravitational tugging on the star. Another way of detecting an exoplanet is using gravitational microlensing, which involves observing the gravitational bending of light of a source star. Differential photometry is another way of detecting exoplanets. Using differential photometry one can observe the transit of the exoplanet, by generating a light curve to see the temporary dimming of starlight due to a planet passing in front of the star. By examining a large sample of stars, one could detect a possible exoplanet, through the short-periodic dimming of stars. The first exoplanets discovered, hot Jupiters, were large, close to their star, with a short orbital period. All of these techniques could be used to further characterize properties of the star. [1] Due to the technology available, this study will only be using differential photometry to observe the transit of the exoplanet Qatar-1b. Using differential photometry, one could calculate a value for normalized planet radius, orbital velocity, transit duration, and other characteristics of the exoplanet and star. This study is a mode of searching for other forms life in our universe. While in addition, it helps us search for planets similar to Earth that could be habitable to humans. In order to be considered habitable to humans, the planet needs located in proximity to its star, so that there is liquid water, and a similar gravity. The Kepler Mission focuses on this search.

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## II. Methods and Materials

Using a variety of databases for known exoplanets one could predict when the transits would happen for certain exoplanets, at a given time and location on Earth. Using the coordinates associated with the Paul and Jane Meyer Observatory in Clifton, Texas, a list of possible transit times were collected. We would try to take data for an hour before ingress all the way until an hour after egress. Ingress, and egress are events that are defined as the start and end of the transit respectively. Figure 1 shows these events and shows the corresponding event on the light curve.

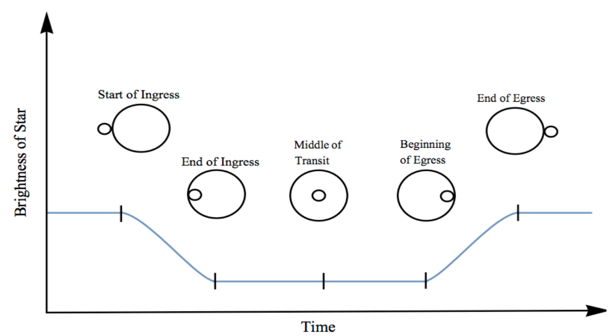


Figure 1 illustrates the specific parts of the transit, and shows the corresponding event on the light curve.

It was important for our star to have an apparent magnitude in between 10-14 Vmag, and our transit to have a depth of at least 10 millimag, which corresponds to a 1% change in flux.

Qatar-1b had an apparent brightness of 12.84 Vmag, and 2.04% change in flux. The transit of Qatar-1b was predicted to occur from 04:27 to 06:04 UTC on June 26$^{th}$, 2015. Data was collected from 03:34 to 06:04 UTC.

Using the ProEm camera attached to the .6 meter telescope to take a continuous stream of pictures of the host star during the transit. The telescope's field of view recorded a 15° x 15° section of the night sky. The filter type, and exposure time used for the pictures depends on the type of the star, and the apparent magnitude of the star. For the transit of Qatar-1b, we used the BG40 filter and an exposure time of 30 seconds.

In addition to the frames taken for the duration of the transit, a light curve cannot be generated without calibration frames. There are three types of calibration frames: biases, darks, and flats. Thirty frames of each calibration type were taken, except for darks, with 60 sets for the two different exposure times. Bias frames account for electrical noise within the CCD chip inside the camera, and have no exposure time. The camera is cooled to combat a good portion of the thermal noise, and nitrogen is used to prevent ice crystals from forming. Dark frames are taken to account for any remaining thermal noise. Darks were taken at two different exposure times, one to calibrate the light frames (30 seconds), and one to calibrate the flat frames (10 seconds). Flat frames account for physical imperfections such as dust particles on the camera lens, frame lens, or the mirror that may distort our image in any way. The flat frames were taken with an exposure time of 10 seconds.

## III. Image Analysis

After all the pictures were taken, a program called AstroImageJ 3.1 was used to generate a light curve. Master calibration frames were created with AIJ. AIJ can correct an image or a large stack of images (in our case), with these master calibration frames. After correcting all of the images taken of the transit, aligning our target star, and comparator stars, a light curve is generated in AstroImageJ, and can be seen in figure 2.

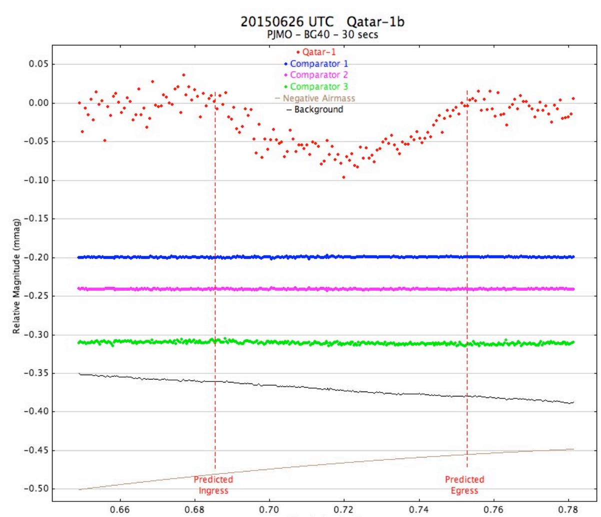


Figure 2 shows the light curve of the transit of the exoplanet Qatar-1b in red. Comparator stars are also graphed for reference.

## IV. Theory

### A. *Uniform Source*

A light curve equation modeling the transit of a planet assuming a uniform source, assumes that brightness of the star is constant to a distant observer. By assuming a star of constant brightness, the dip in the light curve is modeled solely on the star's area obscured by the planet. The equations modeling the transit (uniform source and limb darkening) come from [2]. The actual equation for a light curve is given by the piecewise *F(t)* below.

$$F(t) = \begin{cases} 1, & 1+p < z(t) \\ F_1(t), & |1-p| < z(t) \le 1+p \\ 1-p^2, & z(t) \le 1-p \end{cases} \tag{1}$$

$$F_1(t) = 1 - \frac{1}{\pi}\left[p^2\kappa_0(t) + \kappa_1(t) - \sqrt{\frac{4z(t)^2 - (1+z(t)^2-p^2)^2}{4}}\right] \tag{2}$$

$$\kappa_0(t) = ArcCos\left[\frac{p^2 + z(t)^2 - 1}{2pz(t)}\right] \tag{3}$$

$$\kappa_1(t) = ArcCos\left[\frac{1-p^2+z(t)^2}{2z(t)}\right] \tag{4}$$

$$z(t) = \sqrt{v^2(t-t_m)^2 + \eta^2} \tag{5}$$

$$v = \frac{1\sqrt{(1+p)^2 - \eta^2}}{dt} \tag{6}$$

In the above equations, *z(t)* is the center-to-center planet to star distance, this was made a function of time to model our light curve data. The normalized radius, *p,* is equal to the radius of the star divided by the radius of the planet. The velocity of the planet is *v*. The impact parameter, *η,* is defined as the vertical distance from the center of the star to path the planet travels across the star. In our calculations, and modeling, we treat the impact parameter as a constant value. The time duration of the transit, *dt*, is in seconds. Figure 3

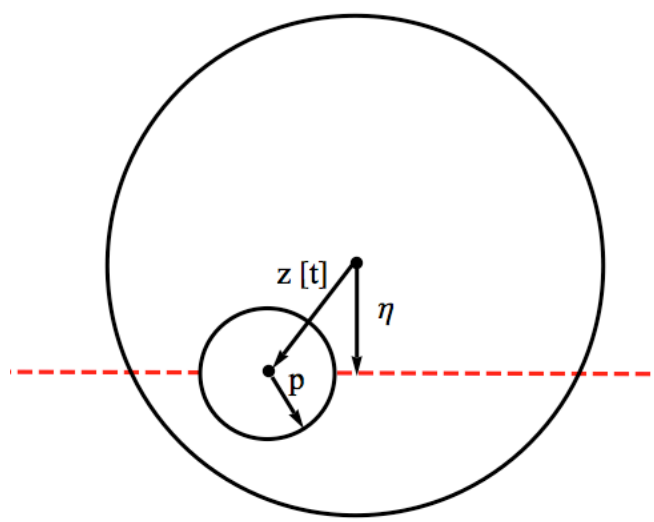


Figure 3 illustrates the physical meaning to the parameters in our equations, star center to planet center, *z*, impact parameter, *η,* and the normalized planet radius, *p.*

illustrates these parameters to show their physical meaning.

### B. *Limb-Darkened Source*

The next condition to take account for is a limb-darkened star, meaning account for the fact that a star is brightest at the center. Below are the equations for a quadratic model for the intensity of the star used to create a light curve for a limb-darkened star. The equation is specifically for planets with normalized radiuses of around 0.1. The model is quadratic specifically in $\mu$, which is equal to $\sqrt{1-r^2}$. The actual equation for the light curve is again given by *F(t),* below.

$$I(r) = 1 - \gamma_1(1-\mu) - \gamma_2(1-\mu)^2 \tag{7}$$

$$F(t) = \begin{cases} 1, & z(t) > 1+p \\ F_1(t), & 1-p < z(t) < 1+p \\ F_2(t), & z(t) \le 1-p \end{cases} \tag{8}$$

$$F_1(t) = 1 - \frac{L(t)}{4\pi\Omega}\left(p^2 ArcCos\left[\frac{z(t)-1}{p}\right] - (z(t)-1)\sqrt{p^2-(z(t)-1)^2}\right) \tag{9}$$

$$F_2(t) = 1 - \frac{p^2 L_2(t)}{4\Omega} \tag{10}$$

In the above equations, $L(t) = (1-a)^{-1}\int_{z(t)-p}^{1} I(r)2r\partial r$, $a = (z(t) - p)^2$, and $L_2(t) = (4z(t)p)^{-1}\int_{z(t)-p}^{z(t)+p} I(r)2r\partial r$. While $\Omega = \frac{1}{4} - \frac{\gamma_1}{12} - \frac{\gamma_2}{24}$, [3] and $\gamma_1 = 0.595$ and $\gamma_2 = 0.1155$ for Qatar-1 [source].

## V. MODEL FITTING

Once we exported our data out of AstroImageJ into *Mathematica,* and from there the we used a function to vary certain parameters in our equations, specifically, $p$, $t_m$, $dt$, and $\eta$. Then using a variance function or the least square method to find the best fit, with the least possible error. The model fit for our uniform source analysis is shown in figure 4, and the model fit for our limb-darkening model is shown in figure 5. Both of the light curves as a whole had followed a downward trend similar to the airmass over night. We fitted a polynomial to our light curve to properly account for this trend in our data.

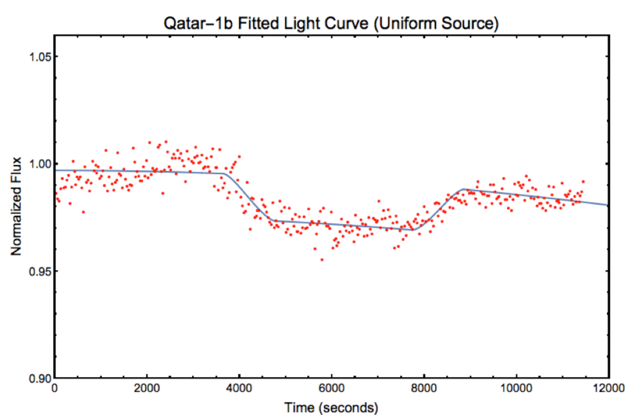


Figure 4 shows the uniform source light curve equation fitted to our model.

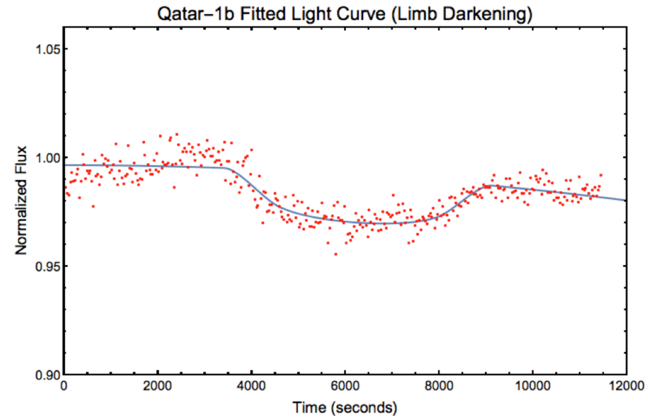


Figure 5 shows the limb darkened source light curve fitted to the data we took.

## VI. RESULTS

### A. *Physical Characteristics from Fit*

| Parameter | Fitted value (uniform source) | Fitted value (limb darkened) | Published value |
|---|---|---|---|
| $p$ | 0.145 | 0.145 | 0.1455 ± 0.0015 |
| $dt$ | 5200 seconds | 5690 seconds | 5802 ± 1.382 seconds |
| $\eta$ | 0.67 | 0.68 | 0.696 ± 0.024 |

The physical characteristics in the table above come from the fits with the least amount of error.

### B. *Physical Characteristics calculated from Fit*

From the physical characteristics found from our fit, we were able to calculate to some physical characteristics of the exoplanets from our other values found, by making a few assumptions. When we calculated the density of the star, $\rho_s$, we assumed a value for the period of the exoplanet orbit from [4]. When we calculated the inclination angle of the orbit, *i,* we assumed a value for the orbital semi-major axis, and a value for stellar radius from [4]. And when we calculated the radius of the planet, we assumed a value for the radius of the star from [4].

| Parameter | Calculated value from fit | Published value [4] |
|---|---|---|
| $\rho_s$ | 2371.33 kg/m$^3$ | 2143.2 ± 169.2 kg/m$^3$ |
| $i$ | 83.62$^o$ | 83.47$^o$ ± 0.38$^o$ |
| $r_p$ | 1.189 $R_J$ | 1.164 ± 0.045 $R_J$ |

## VII. DISCUSSION

### *A. Qatar-1b: a hot Jupiter*

The two most important factors in characterizing a planet, as a hot Jupiter are its large size, and its short orbital period. Obviously Qatar-1b is a large star; it's slightly larger than Jupiter according to our values, and published values. In the calculations for density of the star, we assume the orbital period to be 1.42 days from [4]. This is a super short period, especially when in comparison to the Earth's orbital period of 365 days, and to Mercury's orbital period of 88 days.
Considering these facts, it's safe to consider Qatar-1b as a hot Jupiter.

### *B. Possible Sources of Error*

We added a polynomial with the coefficients to our light curve equations to account for the airmass, and background causing the decreasing flux in the light curve. Using the variance equation we made to reduce the error, we attempted to fit the backgrounds effect by just reducing the error.

Another possible source of error in our data is in the way we defined our velocity. We only took into account the linear distance traveled in front of the star when, in actuality, the planet is actually traveling the arc length of a circle.

### *C. Future Research*

When dealing the airmass, AIJ gives us data for the change in the atmosphere. By exporting that data, and fitting that data can help us find a better polynomial for this, which could help us to find more accurate values for our fit parameters.

A lot of mathematical work could be done to account for this arc length traveled, however it would be very difficult because one would have to assume the orbital semi-major axis. Using Doppler velocimetry, we could attempt to find out other physical parameters, and calculate the semi-major axis and from those physical parameters.

One of the most important ways to improve our data however though, is to take more data. Observing a transit for Qatar-1b could help us improve our values. However, it would be more beneficial to take data for a different exoplanet, that way we could see if the errors in our data deal with Qatar-1b, or all exoplanets which points that our real problem lies in the analysis.

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