# Exoplanet Observation and Analysis Using 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°.**

***Index Terms*—Exoplanets, differential photometry, hot Jupiter, limb darkening**

## I. INTRODUCTION

The study of exoplanets has increased in recent years, gaining more statistical data in order to draw conclusions about planets outside of our solar system. The first exoplanet was confirmed in 1995, and since then there have been many projects dedicated to finding more. Satellites such as the Kepler spacecraft have been observing parts of our sky for years. Their observations provide possible stars to observe, few of which contain exoplanets. One method of collecting data is differential photometry, where the relative flux of a star is measured and a light curve can be plotted. The dimming of the star corresponds to a transiting exoplanet, and a dip in the light curve indicates transit. Through Earth's atmosphere, large exoplanets are the easiest to detect through differential photometry. Therefore, many discovered objects have turned out to be hot Jupiters, such as Qatar-1b. Doppler spectroscopy can be used to detect and confirm exoplanets, a method that uses radial velocimetry to measure the red and blue shifts of the sun/planet system.

## II. OBSERVATION

Transit databases used for observation include the Swarthmore Astronomy and Exoplanet Transit Database sites. Exoplanet transits were chosen based on their right ascension and declination coordinates, relative flux, and apparent brightness. A minimum value of 10 millimag change in flux is required for a successful transit light curve. Stars could not have lower than 8 Vmag or higher than 15 Vmag in apparent brightness.

Observing exoplanet transits was done with a Princeton Instruments ProEm camera on a .6 meter telescope at the Paul and Jane Meyer Observatory near Clifton, Texas. The telescope captures a 15°x15° field, and data was collected using thirty second exposures and a BG40 filter. These settings were determined by photon counts obtained by the CCD chip, where a mean of about thirty thousand was preferable. The focus had a setting of 116797, where full width half max values of pictured stars ranged from 2.5 to 3.

Master calibration was done by building darks, flats, and biases. Darks were captured to calibrate thermal noise within the CCD chip. Two sets of darks were taken; one set had ten second exposures to build flats and the other used a thirty second exposure time. Flats calibrated any imperfections physically present on the telescope lens and mirrors, a ten second

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exposure was used for that set. Biases calibrated the noise present on the CCD chip and had no exposure time. All masters were built using median values of sets of 30 different images.
QATAR-1b observation occurred Thursday, June 26, 2015 from 3:34 to 7:00 UTC. A window of time for pre- and post-transit data collection was accounted for, in order to have a clear image of the star's light curve without obstruction. A total of 353 images were processed and analyzed for a transit of ninety-six minutes.

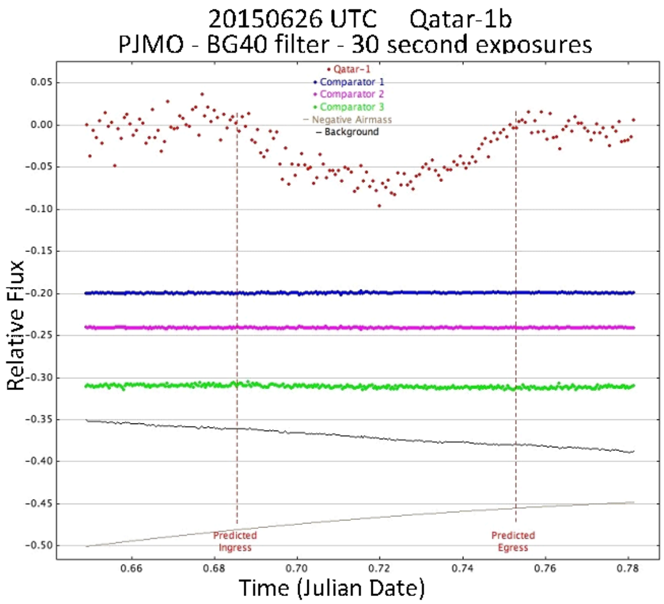


Fig. 1 Light curve obtained from observation of transit.

## III. Analysis

Processing the CCD images was done on AstroImageJ 3.1. Through the data processor, master calibration files for the bias, dark and flat images were built. Then the light images of Qatar-1 calibrated with the master files to subtract and divide out the noise.

Multi-aperture alignment stacked the light images into a single aligned sequence using comparator stars. Using multi-plot, a light curve of Qatar1 and nearby comparator stars was created. Comparator stars were chosen based on similar apparent magnitudes with QATAR-1b and small changes in flux. In order to make the light curve of Qatar1 more pronounced, a scaling factor of 8 was applied and it was shifted by -1.5. Shifting the curve down allowed for the pre-ingress and post-egress limbs to rest at zero relative flux. Comparator light curves were scaled and shifted down to provide constant and even lines. Airmass and atmospheric noise were also plotted in order to account for trends that affected our data (Fig. 1). Using the measurements table on AstroImageJ, data was compiled and exported as a usable file for import in Mathematica.

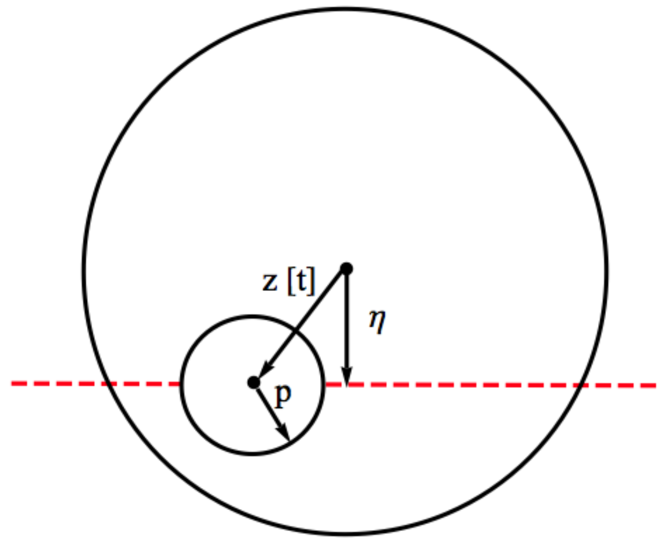


Fig. 2 Graphic representation of *p*, *z[t]*, and *η*.

## IV. Modeling

### A. Uniform Source

In order to fit our data, we used equations outlined in the Mandel and Agol[1]. They use a piecewise for describing different phases in the light curve: pre-ingress, ingress, transit, egress, and post-egress. To describe these bounds, they are defined in terms of *z*, which we transformed to be time dependent *z[t]*, and *p* (Fig. 2).

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

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

The function *z[t]* is defined as center to center distance from planet to star, where $v$ equals the velocity, *tm* equals the coordinate time of mid-transit and $\eta$ equals the impact parameter. Inside F[t], $\kappa_0 = cos^{-1}\left[\frac{p^2+z^2-1}{2pz}\right]$ and $\kappa_1 = cos^{-1}\left[\frac{1-p^2+z^2}{2z}\right]$.

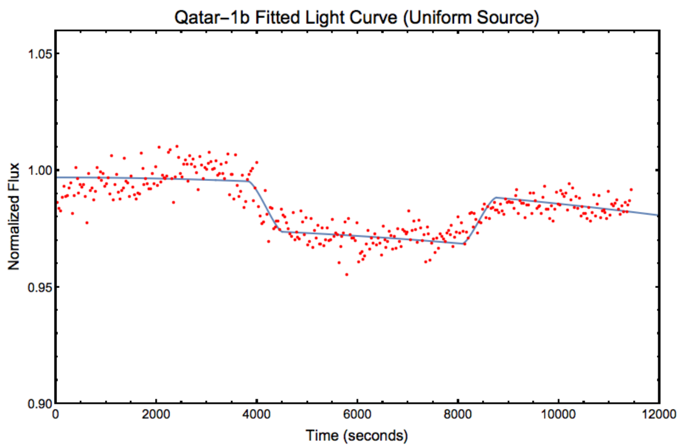


Fig. 3 Uniform source model fit with Qatar-1b transit data.

## B. *Small Planet Limb Darkening*

A more exact way to model exoplanet light curve is through small planet limb darkening. Assuming a normalized planet radius of about equal to .1, it applies a limb darkening model $I[r] = 1 - \gamma_1(1-\mu) - \gamma_2(1-\mu)^2$ that is quadratic in μwhere it equals $\sqrt{1-r^2}$.

$$\text{Flux}(t) = \begin{cases} 1, & z[t] > 1+p \\ F_1[t,p], & 1-p < z[t] < 1+p \\ F_2[t,p], & z[t] \leq 1-p \end{cases} \quad (3)$$

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

$$F_2[t,p] = 1 - \frac{p^2 L_2[t,p]}{4\Omega} \quad (5)$$

where $L[t,p] = (1-a)^{-1}\int_{z[t]-p}^{1} I[r]\, 2r\, dr$, $a = (z[t]-p)^2$ and $L_2[t,p] = (4\, z[t]p)^{-1}\int_{z[t]-p}^{z[t]+p} I[r]\, 2r\, dr$. The constant Ω is defined as $\Omega = \frac{1}{4} - \frac{\gamma_2}{24} - \frac{\gamma_1}{12}$ , and $\gamma_1 = 0.595$ and $\gamma_2 = 0.1155$. Using these equations, we used a manipulate function to vary *p*, *dt*, and $\eta$. In order to determine the best values for each of these parameters, we created a variance function or least squares method and adjusted the values to get the lowest error.

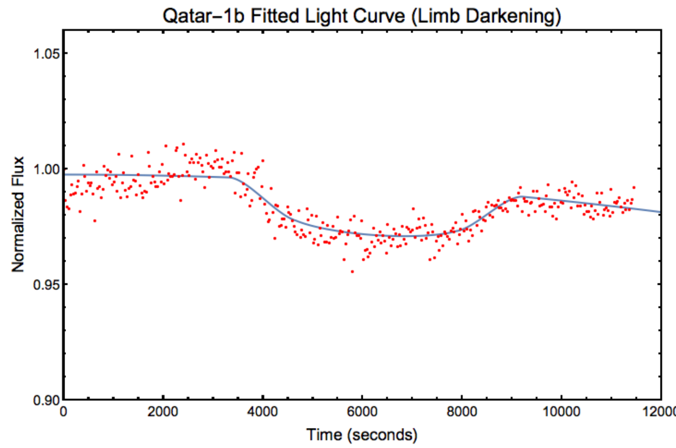


Fig. 4 Small planet limb darkening model fit with Qatar-1b transit data.

# V. RESULTS

## A. *Model Fit Values*

| | Uniform Source Fit | Limb Darkening Fit | Published Values[2] |
|---|---|---|---|
| **P** | .145 | .145 | 0.1455±0.0015 |
| **dt (seconds)** | 5200 | 5690 | 5802±1.382 |
| **η** | .67 | .68 | 0.696±0.024 |

The above results are what we fit from using our models.

## B. *Calculated Parameters*

| | Uniform Source Fit | Limb Darkening Fit | Published Values[2] |
|---|---|---|---|
| **ρ (kg/$m^3$)** | 3106.84 | 2371.33 | 2143.2±169.2 |
| **i (degrees)** | N/A | 83.49 | 83.47±0.38 |

Assuming an orbital semi-major axis for Qatar-1b, both density of Qatar-1 and the inclination angle, *i*, could be calculated. We used Kepler's 3rd law and a velocity equation using circumference of orbit in order to create a density equation.

$$\rho_s = \frac{3P\tilde{v}^3}{8\pi^2 G} \qquad (6)$$

## VI. Discussion

Based on the calculated normalized radius, Qatar-1b matches the features of a hot Jupiter, assuming the radius of Qatar-1. Qatar-1b's normalized radius is larger than Jupiter's normalized radius, which is 0.100.

Adding limb darkening to the model resulted in more accurate values for the impact parameter and density. Normalized radius of Qatar-1b is dependent on the depth of relative flux, and therefore did not vary much between the uniform source model and the limb darkened model.

## VII. References


[1] K. Mandel and E. Agol, "Analytic Light Curves for Planetary Transit Searches," *Astrophys. J. Lett.*, vol. 580, pp. L171–L175, Dec. 2002.

[2] K. A. Alsubai, N. R. Parley, D. M. Bramich, R. G. West, P. M. Sorensen, A. C. Cameron, D. W. Latham, K. Horne, D. R. Anderson, D. J. A. Brown, L. A. Buchhave, G. A. Esquerdo, M. E. Everett, G. Fürész, C. Hellier, G. M. Miller, D. Pollacco, S. N. Quinn, J. C. Smith, R. P. Stefanik, and A. Szentgyorgyi, "Qatar-1b: a hot Jupiter orbiting a metal-rich K dwarf star," *Mon. Not. R. Astron. Soc.*, vol. 417, no. 1, pp. 709–716, Oct. 2011.



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