Search for Extra-Solar Planets using the Transit Method

by

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Abstract

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The search for extra-solar planets is a relatively new field that has only existed for less than two decades. The transit method requires someone to observe a star during the transit of an exoplanet and document the decrease in luminosity due to the planet. From this decrease in luminosity, several characteristics of the planet can be determined such as radius and the orbital size.

Qatar-1 was the star being observe, which is located near the Big Dipper. All CCD images were taken by the Rapid Response Robotic Telescope (RRRT) which is owned and operated by NSU and located at Fan Mountain, Va.

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Introduction

What are Extra-Solar Planets?

Extra-solar planets or exoplanets are planets that are on our solar system. Finding exoplanets are essential in the search for extraterrestrial life. The search for exoplanets is a relatively new field of study since the first exoplanet was discovered in 1995, which was discovered by Michael Myer and Didier Queloz. Since then there have been hundreds of discoveries and more and more are found every year. Most of the discoveries have been very big Jupiter like planets that orbit very close to the parent star, while there have been a few smaller planets orbiting in the habitable zone found.

Methods of Finding Exoplanets

There are several ways to detect an exoplanet. The first of which is the radial velocity method. When a planet orbits a star, the two objects rotate around their combined center of mass. When the center of mass is far enough from the center of the star the star will begin to wobble about the center of mass. This wobble produces a measureable doppler shift and from the doppler shift the mass and orbital size of a planets can be found. Another method of finding an exoplanet is the astrometric method. This method is very similar to the radial velocity method but instead of relying on a doppler shift it relies on the monitoring the change in position of the star due to the wobble. Yet another method of finding an exoplanet is gravitational microlensing. In order for this method to work two stars have to line up one behind the other so that the gravity of the first star bends the light of the second allowing us to see the planets orbiting the first star. The last of the methods to be discussed is the transit method which will be discussed in much detail throughout the rest of the paper.

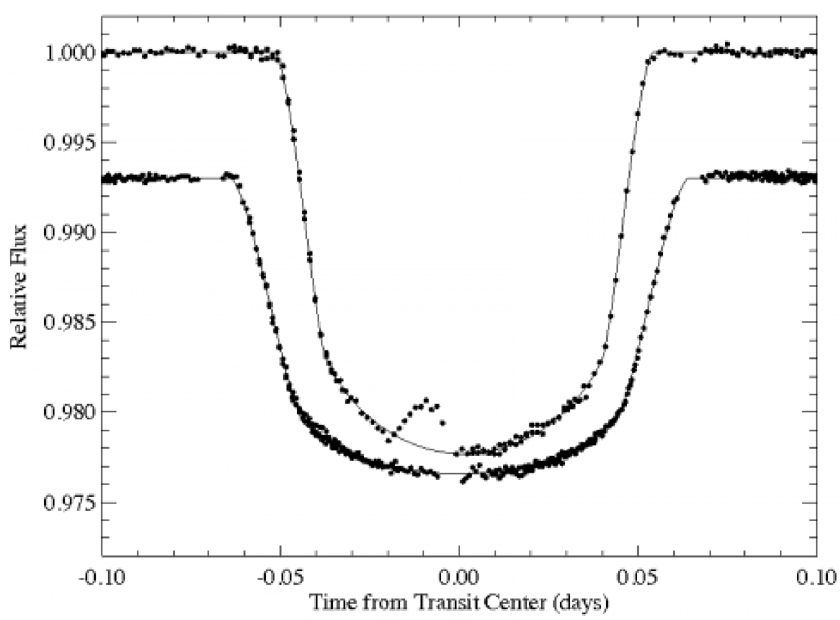
Transit Method

Obtaining a Light Curve

To obtain a light curve, an exoplanet has to be observed as it orbits in front of the parent star and the decrease in luminosity due to the planet's transit has to be recorded. The luminosity of several other stars are compared to the chosen stars luminosity to make sure the change in luminosity is due to an exoplanet and not other factors. The difference between the constant star and the variable stars creates a light curve. From this decrease in luminosity the radius, semi major axis, and orbital inclination can be found.

What the Light Curve Tells Us

The light curve from an exoplanets transit tells us more about a planet than many other forms of detecting exoplanets. From the sample light curve the four



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phases of a transit can be seen. The first phase is first contact, this is where the planets begins to make it way into the visible disk of the star and begins the transit. This can been seen as the beginning in the change in flux on the graph. The second phase is called second contact. This is where the planet is fully within the visible disk of the star and can be seen as the flattening at the bottom of the curve. The point between first and second contact is known as the ingress. The third phase is called third contact, this where the planets begins to leave the visible disk of the star and can be seen as the rise of the flux on the graph. The last phase is fourth contact, which is when the planets is no longer inside a part of the visible disk of the star. This can be seen as the return to normal flux on the graph. The part between third and fourth contact is known as the egress (Haswell).

From the light curve the radius, semi major axis, and the orbital inclination of the planet with respect to the parent star can be found from the light curve. The square of the ratio between the planet's radius and the star's radius is equal to the ratio between the change in flux and the normal flux of the star. This can be shown using the equation

$$\frac{\Delta F}{F} = \frac{R_p^2}{R_*^2}$$

This equation does not take into account limb darkening and is therefore only an approximation. The characteristics to find is the semi major axis, which can be found using Kepler's third law.

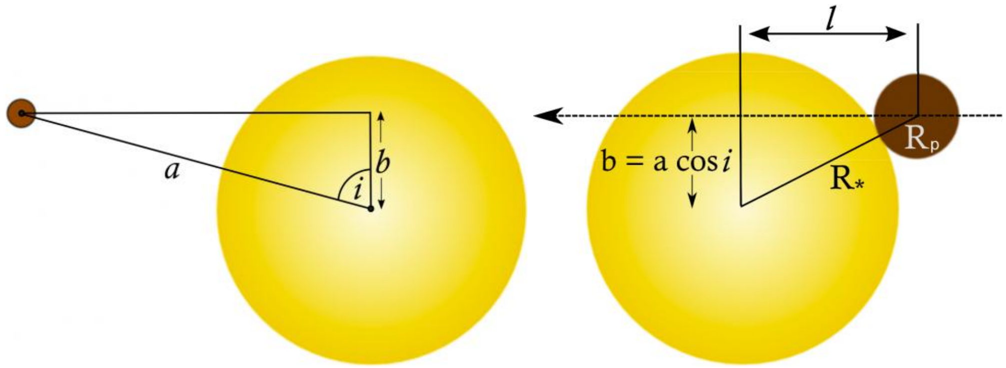
$$\frac{a^3}{P^2} = \frac{G(M_* + M_P)}{4\pi^2}$$

Although the mass of the planet is unknown, one can assume that the mass of the planet is much, much less than that of the star. Therefore the previous equation can be rewritten as

$$a \approx \left[GM_* (\frac{P}{2\pi})^2 \right]^{1/3}$$

, which can give a relatively accurate approximation of the semi major axis. Now knowing the semi major axis, the impact parameter, or orbital inclination can be found. The impact parameter is the distance the planet is above the center of the star at mid transit. The impact parameter is directly related to the orbital inclination

$$b = \cos i$$



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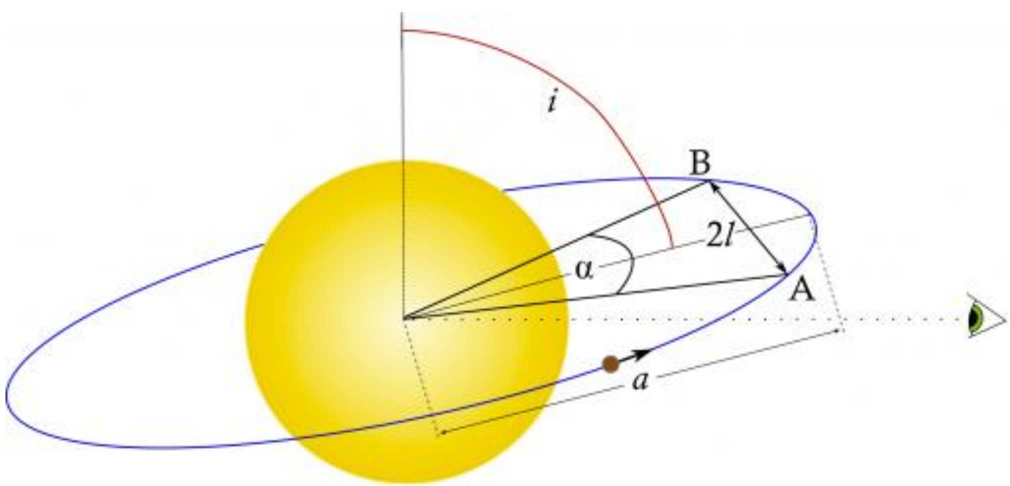
$$l = \sqrt{(R_* + R_p)^2 - a^2 \cos^2 i}$$

Where b is the impact parameter and *i* is the inclination. Assuming the planets transits at a constant speed, *l* corresponds to the time from start to mid transit. Knowing the length of the transit and the orbital period, the inclination can be found and therefore the impact parameter.



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$$T_{durration} = \frac{P\alpha}{2\pi} \rightarrow \sin(\frac{\alpha}{2}) = \frac{l}{a} \rightarrow \alpha = 2\sin^{-1}(\frac{l}{a}) \rightarrow T_{duration} = \frac{P}{\pi}\sin^{-1}(l/a)$$

$$T_{durration} = \frac{P}{\pi}\sin^{-1}(\frac{\sqrt{(R_* + R_p)^2 - a^2\cos^2 i}}{a})$$

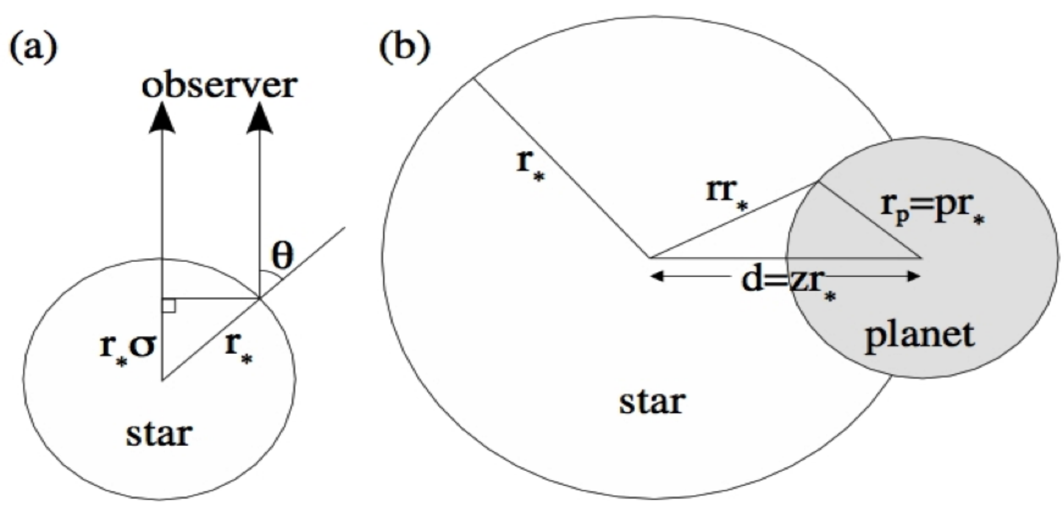
but when $a \gg R_{star} \gg R_{planet}$ then α becomes a small angle and the equation can be simplified to

$$T_{duration} \approx \frac{P}{\pi}\sqrt{\left(\frac{R_*}{a}\right)^2 - \cos^2 i}$$

,and with a little bit of algebra the orbital inclination can be found (Haswell).

Limb Darkening and Air Mass Extinction

Limb darkening is an effect of the geometry and the opacity of the star. As you move farther to the edges of the disk, the more of the star's atmosphere it has to travel through to escape the star. Because of this the star becomes redder or darker towards the limbs.



$$F = 1 - \frac{I^*(z)}{4\Omega}\left[p^2\cos^{-1}\left(\frac{z-1}{p}\right) - (z-1)\sqrt{p^2 - (z-1)^2}\right]$$

Due to the fact that the star gets brighter as it moves inward, the light curve will have a trough between second and third contact. The equation gives you flux as a function of the distance between the centers of the two bodies (as the picture depicts). This function is important in fitting the light curve with a trend line (Agol and Mandel).

Air mass extinction is a slight drop in luminosity due the amount of air that a given object is being observed through. The closer the star is to being directly overhead, the less air the object is being observed through and therefore less light is lost. As an object moves throughout the night, the air mass will change and can cause a trend to data points

Equipment

Telescope

The telescope used to take the images was the Rapid Response Robotic Telescope (RRRT). The RRRT is located on Fan Mountain, which is just outside Charlottesville, Va. And is owned and operated by Norfolk State University (NSU). The telescope is a 24'' Richey-Chretien reflecting telescope with a f/8.0 focal ratio.

The RRRT's main use is to monitor gamma ray bursts. When there are no GRBs to observe the RRRT will monitor a range of objects or events ranging from exoplanets to near earth objects (nsu.edu).

CCD Camera

Charged couple devices (CCDs) have become the preferred device to capture astronomical images. They have many advantages, biggest of which is their consistency and ability to easily take images with different exposure times. A CCD chip is set up in a two dimensional array (checkerboard) of photon detectors, or photosites. Each photosite is a capacitor so when a photon strikes it, the energy from the photon causes an electron to jump into an excited state and is then caught in an electron well. The number of electrons in the well creates a voltage, which can thereby be converted into a digital signal, or information. When a CCD is read out, each photosite is given a specific value, which corresponds to a pixel in a picture once brought up on a computer screen. This initial image is called the raw image, which includes all the imperfections in the image, which can be factored out later. The array is covered in a thin layer of silicon, which is fairly reflective to low energy light, infrared and so on. For this reason a typical CCD mostly registers visible light. Light can also be run through filters to only pick up certain wavelengths, and once several images of primary colors are added together you can get color images (Berry and Brunell).

CCDs are by no means perfect, but their flaws are usually consistent. Because of this consistency, we are able to factor out the imperfections in the chip and obtain very clear images. The general flaws of a CCD are dark current, read out bias, vignetting, and dust particles on the optical system. There are several different ways the factor out imperfections, each more elaborate and time consuming than the last (Berry and Brunell).

The first is creating a dark frame, which enables us to measure and subtract out dark current. A dark frame is taking an exposure with the shutter of the camera closed and the telescope capped. By taking an exposure where no light is let in can compensate for the electron well of the photosite not being zeroed out, and once registered and converted into a digital signal can give the pixel associated with that photosite a brighter appearance. This is known as the dark current. There are other factors to dark current, such as temperature of the CCD itself. As explained earlier, electrons end up in the electron well when then have jumped to an excited state due to energy from incoming photons. The ambient temperature of the CCD can also cause electrons to hop into the well, thereby increasing the dark current. By doing this several times during a viewing period we can take a mean value of each pixel and subtract out that value from each pixel. This mean value image of the dark frames in called the master dark frame, which in most cases can be applied to all the raw images taken over the viewing session (Berry and Brunell).

The next step in eliminating impurities in the raw image is to create a flat frame. A flat frame helps counteract vignetting and dust donuts. Vignetting is caused by light not reaching the entire CCD chip properly. In a flat frame image it will generally look like a dark fade in the corner of the image. Dust donuts are pretty self-explanatory; dust particles create a dark ring in the flat frame image. To create a flat frame, you must illuminate the CCD until the photosites are filled to roughly half the capacity. Flat frames can be tricky to create and there are several methods to create them. The most common two are to either create a light box are dome flats. These two are very similar and the size of the telescope is the determining factor.

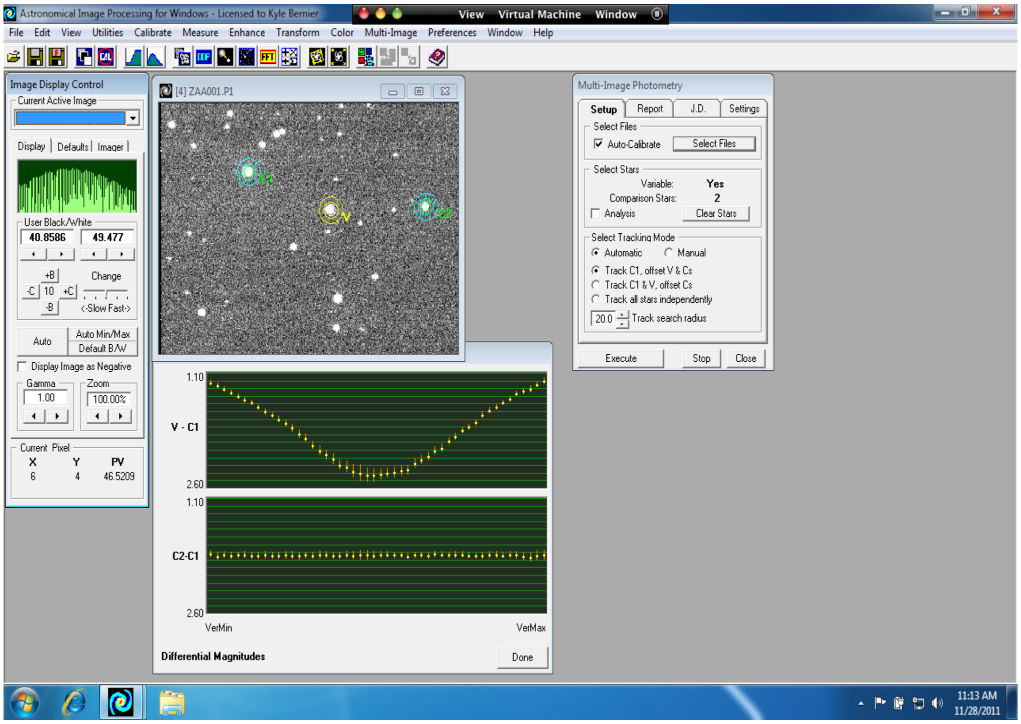
For smaller telescopes, a light box with a uniformly light distribution can be placed in front of the telescope. Dome flats are the same idea but putting a box in front of giant scientific telescopes is a little impractical. The next way is to take flats right as the sun is going down or coming up. This requires perfect timing but requires less equipment and effort. The last is to take an enormous amount of images of the night sky and then take the mean of all those images. This requires no light box but takes a significant amount of computation. The RRRT used a light box attached directly to the camera. By creating as many flat frames as dark frames you can take into account the visual impurities and subtract them out in the same manner as dark frames (Berry and Brunell).

The final step in the filtering process is creating a bias frame. A bias frame is a zero time exposure, which is meant to take into account the possible charge a pixel could pick up from the digitalization process. Depending on the scenario, you can either use just a single bias frame or create a master bias frame (Berry and Brunell).

Once all of the effects have been taken into account the image can be completely filtered giving us the best resolution we can obtain with the equipment

AIP4WIN

Astronomical Image Processing for Windows (AIP4WIN) is an image-processing program specifically designed to analyze astronomical events. AIP4WIN has the ability to create master frames for every type of CCD correction. AIP4WIN also has the ability to monitor several stars simultaneously and document their pixel values. This is very helpful when obtaining a light curve since AIP4WIN can monitor the variable star and the constant stars and produce a text file with the difference in luminosity between the variable and constants in every image. The text file can then be imported into several database programs to produce a light curve.



Snapshot of AIP4WIN 1

Results

Qatar-1

Qatar-1 has a right ascension and declination of 20h13m32s and +65h09m43s. Qatar-1 is located roughly 550 light years away in the Draco constellation, near the big dipper, and is a type K star burning at roughly 4900K (www.st-and.ac.uk). The planet being observed in the light curve is Qatar-1b.

Image Information

This transit was taken on 30 June 2011 between 05:13 to 08:20 UTC (12 to 3 AM local time). All images were taken with a red filter and had 40 second exposure times.

Using AIP4WIN

AIP4WIN was used to create the master dark, flat, and bias frame. Once the master frames were created I was able to run the 180 images through the multiple image photometry feature, which will automatically calibrate the frames with the master frames and track the variable star and constant stars. Once the program was done analyzing the images I was able to import the text file into excel and create a rough light curve from the data points[1].

Fitting the Light Curve

Once I had the data in excel I had to trim the data so that I could import the data to the Exoplanet Transit Database (ETD), which is web site specifically dedicated to fitting light curves. The ETD web site will correct for air mass extinction and limb darkening. The limb darkening variables can be suited to best fit your particular curve depending on how much of trough is in the curve.

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[1] Excel has an import feature that will let you import text files. The feature has a line and delimiter feature so you can import only what you need.

Final Numbers

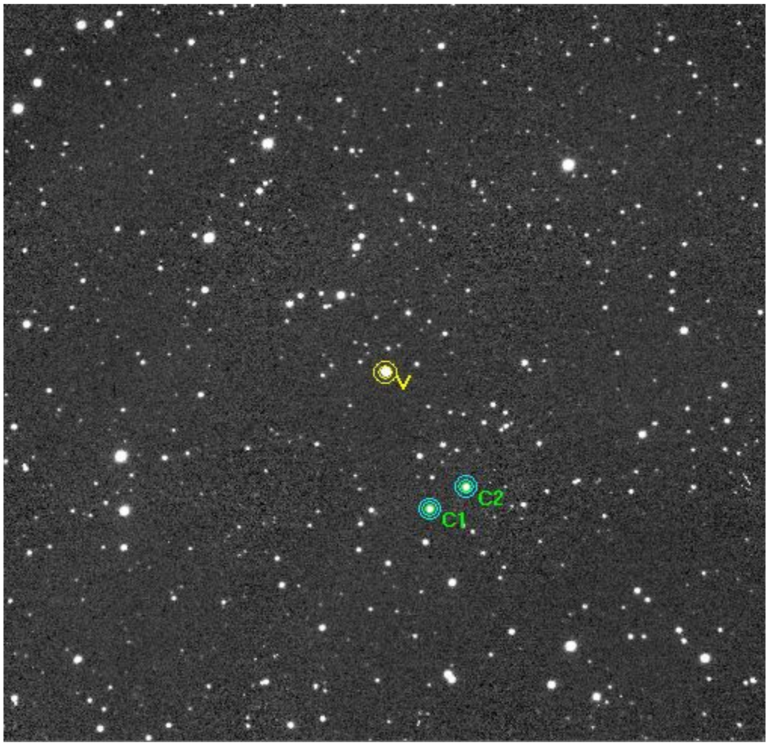
I wrote a simple java program[2] to compute the approximation values based off of the rough curve I created in excel. From my program I was able to determine that the planet a radius 1.066$R_{Jupiter}$, a semi major axis of 0.0234 AU, an orbital inclination of 86.1^{o}, and a transit length of 97.9 min. From fitting the line using ETD I was able to obtain that planet had a radius of 1.155 $R_{Jupiter}$, a semi major axis of 0.0234 AU, an orbital inclination of 83.47^{o}, and a transit length of 98 .8 min +/- 5 min. The current excepted values for Qatar-1b are 1.164 $R_{Jupiter}$, a semi major axis of 0.0234 AU, an orbital inclination of 83.47^{o}, and a transit length of 96.7 min.

Conclusion

I was able to obtain a light curve from monitoring Qatar-1. With the help of some software I was able to confirm the existence of a planet orbiting the star and also calculate some of the characteristics of the planet. The transit method is great method for finding a lot of information about an exoplanet. Coupled with the radial velocity method, almost all of the important characteristics of a planet can be calculate.

[2] Program is in the Appendix

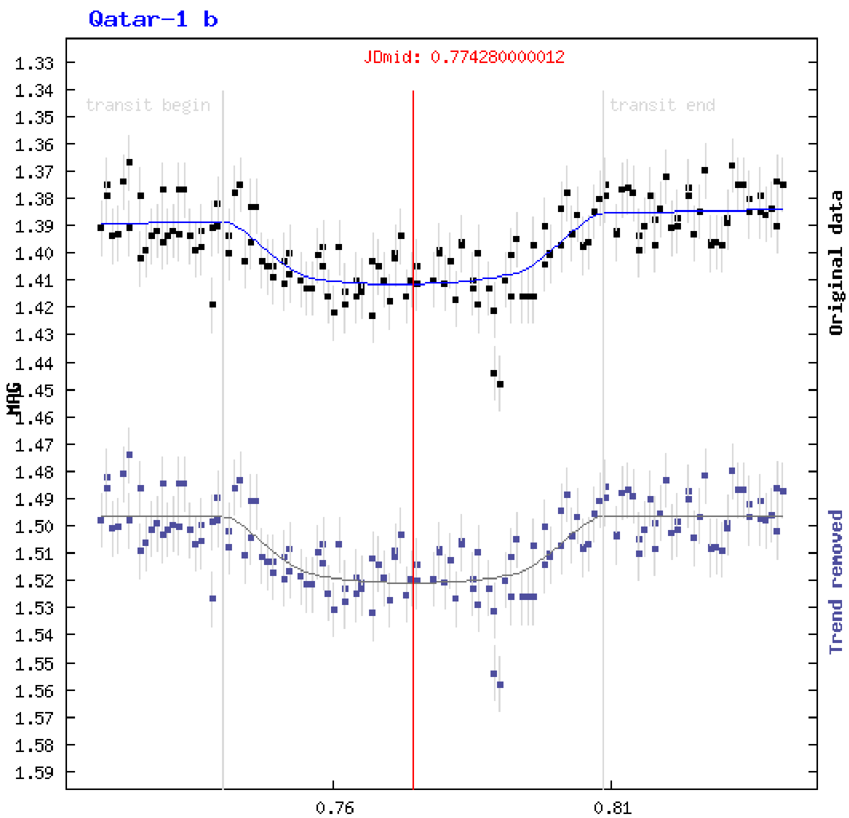
Appendix



Qatar-1(yellow) Constants(blue) 1

Julian_Day	Integr	Filt	(V-C1)	±Sigma	(C2-C1)	±Sigma	(V-Ens)	±Sigma
2455742.718	40	R	-0.651	0.005	0.219	0.007	1.391	0.004
2455742.719	40	R	-0.652	0.005	0.227	0.007	1.375	0.004
2455742.719	40	R	-0.656	0.005	0.23	0.007	1.379	0.004
2455742.72	40	R	-0.647	0.005	0.223	0.007	1.394	0.004
2455742.721	40	R	-0.648	0.005	0.223	0.007	1.393	0.004
2455742.722	40	R	-0.666	0.006	0.199	0.007	1.374	0.004
2455742.723	40	R	-0.652	0.006	0.211	0.007	1.391	0.004
2455742.723	40	R	-0.662	0.007	0.218	0.009	1.367	0.004
2455742.725	40	R	-0.646	0.005	0.217	0.007	1.402	0.004
2455742.725	40	R	-0.658	0.005	0.215	0.006	1.379	0.003

Snapshot of data in excel 1



Fitted Curve 1

$$F = 1 - \frac{I^*(z)}{4\Omega}\left[p^2 \cos^{-1}\left(\frac{z-1}{p}\right) - (z-1)\sqrt{p^2 - (z-1)^2}\right]$$

```
public class CapStone {

	public static double gravitationalConstant = 0.0000000000667;
	public static double pi = 3.14159;
	public static double deltaF;
	public static double magnitude;
	public static double rStar;
	public static double mStar;
	public static double period;
	public static double rPlanet;
	public static double duration;
	public static double semiMajor;
	public static double impactPerameter;

	public static double planetRadius(double a, double b, double c ){
		deltaF = a;
		magnitude = b;
		rStar = c;

		double temp = deltaF*rStar*rStar/magnitude;
		rPlanet = Math.sqrt(temp)/(7.1492*Math.pow(10,7));

		return rPlanet;
	}

	public static double semiMajorAxis( double a, double b){
		period = a;
		mStar = b;

		double temp1 = Math.pow( period/(2*pi) , 2 );
		semiMajor = Math.pow(gravitationalConstant*mStar*temp1, 0.333333
);

		return semiMajor;
	}

	public static double impactPerameter(double a, double b, double c, double
d){
		period = a;
		duration = b;
		semiMajor = c*(1.49597*Math.pow(10,11));
		rStar = d;

		double temp = duration*pi/period;
		double temp1 = Math.pow(temp, 2);
		double temp2 = Math.pow((rStar/semiMajor), 2);
		double temp3 = Math.sqrt(temp2 - temp1);
		impactPerameter = Math.toDegrees(Math.acos(temp3));

		return impactPerameter;
	}

	public static void qatarNumbers(){
		rStar = rStar*6.955*Math.pow(10,8);
		mStar = mStar*1.9889*Math.pow(10,30);
		period = period*3600*24;
		duration = duration*60;
	}

	public static void main(String[] args){

		deltaF = 0.0245;
```

```
            magnitude = 1.388;

            rStar = 0.823;

            mStar = 0.85;

            period = 1.42;

            duration = 98.64;

            qatarNumbers();

            double temp1 = planetRadius(deltaF, magnitude, rStar);
            double temp2 = semiMajorAxis(period,
mStar)/(1.49597*Math.pow(10,11));
            double temp3 = impactPerameter(period, duration, temp2, rStar);

            System.out.println("The radius of the planet is " + temp1+ " Rj");
            System.out.println("The semi major axis is " + temp2 + " AU");
            System.out.println("The impact parameter is " + temp3 + "
degrees");
       }
// It's a very simple program that I wrote specifically for Qatar-1
// The output will give the radius in terms of Jupiter's radius
// The semi major axis is given in AU's
// The impact parameter is given in degrees
}
```

References

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