Photometry Analysis of Exoplanets WASP-80b & HD 189733b

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***Abstract*—This paper will discuss the photometry analysis of exoplanets WASP-80b and HD 189733b. Details will be given about each of the observation runs for the target objects. Photometry analysis was completed using the software AstroImageJ, an online exoplanet database for lightcurve fitting, and a Transit Analysis Package (TAP) with produced lightcurves through the calibrated bias, flat, and dark files. The final results show the stellar info, which was extracted from both exoplanet transits.**

I. INTRODUCTION

AN extrasolar planet, or exoplanet, is a planet orbiting a star (or remnant of a star) beyond our Solar System [1]. With the rapid increase in the number of known planets beyond our own Solar System, important new information is being gathered concerning how planetary systems form and evolve [3]. The discussion of exoplanet research has also paved the way for newer technologies in order to analyze the photometric data of these extrasolar bodies. In addition to these systems being interesting to study in their own right, this increase in knowledge about extrasolar planets helps to inform us about our own Solar System [3].

The summer of 2013 provided the opportunity to analyze two different exoplanet transits at the Paul and Jane Meyer Observatory (PJMO). Using the photometry software, AstroImageJ, an online exoplanet database, and a Transit Analysis Package (TAP) for IDL, the extrastellar planetary info was extracted from the processed transit data. This is also the first summer in the history of the REU program that IDL is used in the data analysis of exoplanets.

II. THEORY

When an exoplanet makes a transit, neither the star nor the exoplanet can be resolved in an angle as seen from Earth. However the transiting planet can be detected indirectly since it blocks part of the star's flux. If the cross-section of the planet is $\pi {R_p}^2$,where R_p is the radius of the exoplanet, and the cross-section of the star is $\pi {R_*}^2$ where R_* is the radius of the star ,then when the planet lies directly between the star and an observer, the star's measured flux F drops by a fractional amount given by Equation 1[2]:

(1)

$$\frac{\Delta F}{F} = \frac{\pi {R_p}^2}{\pi {R_*}^2} = \left(\frac{R_p}{R_*}\right)^2$$

Using this data one can find out the relative sizes of the exoplanet and star with Equation 2. Assuming a uniform luminosity over the star then this is all true. Thankfully in the analysis of the data the model of limb darkening provides a more realistic representation of starlight being blocked by a planet:

(2)

$$\frac{R_p}{R_*} = \sqrt{\frac{\Delta F}{F}}$$

If there is a case where the planet is less massive than the star, its orbital semimajor axis, a_p, is derived from Kepler's third law yielding Equation 3:

(3)

$$a_p = \sqrt[3]{\frac{G M_* P^2}{4\pi^2}}$$

Given this info, the speed of the planet, v_p, can also be derived (assuming circular orbit) using Equation 4:

(4)

$$v_p \approx \frac{2\pi a_p}{P}$$

The combination of transit data and radial velocity provides a large payout of planetary parameters [2]. The inclination angle, i, also gives information concerning the range in which the transit is observed. Equation 5 solves for the inclination angle:

(5)

$$\cos i \leq \frac{R_* + R_p}{a}$$

where a , is the distance between the planet and the star. Unless the planet is a few stellar radii away from its parent star, $\cos i$ must be small for a transit to be observed. Therefore i must be close to 90°.

III. OBSERVATIONS

The camera used for the observations was a Roper Scientific 1300b and the filter set was the Johnson-Cousins photometric standard set purchased from Custom Scientific. Before each observation, research was done using the Extrasolar Planet Transit Finder website [5]. On that website information was given for the next exoplanet transits along with the depth in the drop of the transits. The goals for selecting the exoplanets were that the drop in the flux had to be at least 1% (so it can be noticeable on the lightcurve) and that the star was bright enough (at least 18^{th} magnitude or brighter) to be seen from the telescope. The website also listed the airmass which indicated how high the exoplanet would be during the transit. Ideal choices for the airmass had to be below 2 so that the target object could remain high in the sky.

After checking the previous conditions from the transit finder website, the next process was to go to the open catalogue website and look up the right ascension and declination of the objects [6]. Another piece of information which was given on the website was the spectral type of the host stars. Knowing the spectral type of the stars was useful because it allowed for a better understanding of the makeup of the star and which filters to view the transits through.

The entire WASP-80b transit was captured through the red filter. 60 second exposures were captured of the object until the CCD chip saturated at around 64,000 pixel counts. The CCD chip becomes saturated when the photon count exceeds around 65,000 counts creating faulty exposures. The exposures were adjusted to 40 seconds and continued for half an hour after egress.

The HD 189733b transit was viewed on two separate nights. Faulty data was extracted during the first viewing in which the egress wasn't shown in the processed files. The first observation of HD 189733b was viewed through the V filter because of its bright magnitude of 7.67. 4 second exposures were taken over a period exceeding two hours which included as least thirty minutes before ingress and after egress. The second observation yielded better results. The same exposure times were used as the first viewing but the blue filter was used. The blue filter reduces the brightness of the star by about 1.5 magnitudes. This was done so as to select usable comparator stars when producing the lightcurves.

Figure 1: This is the reference star field used to observe the WASP-80b transit. 60 second exposures were taken during the transit until the CCD chip became saturated and the exposure time was shortened to 40 seconds. The R filter was used to observe this object.

Figure 2:The reference star field for HD 189733b. The V and B filters were used. 4 second exposures were taken.

IV. METHODOLOGY

Once the exposures were captured for all the exoplanet transits the calibration stage could begin. Each of the raw data images went through a process of bias and dark subtraction along with flat division using the AstroImageJ software[8]. The raw images needed to go through this process in order for the lightcurve photometry analysis to be conducted. 30 sets of biases, flats and darks were collected which were comprised of 4, 60 and 40 second darks and 10 second flats.

In order to have a final image that represents data only from the target, stars and sky background, the noise that results from the camera electronics must be removed [4]. This is the purpose of the bias frame. When creating the bias frames, zero second exposures (with the camera shutter closed) should be taken so as to reduce the build up of noise from a longer exposure. The bias exposures are then median combined to produce one single master bias frame.

Dark frames are used to remove the noise within the CCD chip caused by the randomly generated electrons due to the atoms in the material bumping into one another, i.e, "thermal noise" [4]. Before each run, the CCD chip is cooled to -35°C to reduce the thermal noise of the camera by slowing the movement of the free electrons. The dark frames have to be taken with the same duration as the target frames. As the dark exposures are median combined into one master dark frame, the master bias is subtracted from the darks to remove the effects of the noise.

The purpose of the flat frames is to take into account the sensitivity of the pixels on the CCD chip. When taking raw flat images, the system should near the same focus as for when target images are taken, usually infinity [4]. For each filter used, flat frames are taken using a screen, which is evenly illuminated, by a uniform light source. Raw flat field exposures are taken and then afterwards the value of each pixel is normalized. The individual images are dark and bias corrected and then median combined into one master flat frame.

Once the master bias, dark, and flat frames are created the raw target images can be calibrated. Using AstroImageJ the target object files were enabled to do bias and dark subtraction along with flat division on each and every raw target image. As soon as the calibrated files were processed, the photometry analysis began.

Photometry analysis of the calibrated target frames was accomplished with AstroImageJ. Options appropriate for the target were chosen and apertures were selected of the target star and each comparison star. AstroImageJ calculated differential photometry on each frame and plotted the light curve of the transit as well as of the comparison stars. By dividing the flux of the target by the total flux of the comparison stars, sky effects were eliminated, such as transient clouds. The configuration files are saved after the lightcurve plot has been generated and then the data is uploaded to the exoplanet transit database[9]. This will not only produce a lightcurve fit but it will also extract the stellar info of the exoplanet. The lightcurve configuration files and plots were made for both WASP-80b and HD 189733b. Figures 3-5 display the lightcurves, which were produced through AstroImageJ.

Due to the recent publication of the discovery of WASP-80b this year the data wasn't found on the exoplanet transit database. On the contrary, extrastellar planet info was found for the HD 189733b transit data. A text file containing heliocentric Julian date, target flux and the error of the target flux was uploaded to the database and from that data a fit was calculated on the exoplanet.

Since WASP-80b couldn't be analyzed through the online database,the lightcurve plot was fitted with TAP through IDL. The goal was to compare the documented orbital period and stellar radius of the planet with the results of our IDL calculations.

TAP, transit analysis package, is a specialized tool used in the analysis of exoplanet data. The software is implemented through IDL and uses Bayesian probability distributions along with Markov Chain Monte Carlo (MCMC) techniques to run statistics on the data. A Markov chain is a mathematical system, which undergoes transitions from different states. The transitions are between a finite or countable number of possible states and are also random. These techniques are implemented on the data so that TAP can better estimate and fit the lightcurve to the plot and extract the exoplanet properties.

Initially, a text file of the transit must be uploaded through IDL once TAP has been compiled. The format of the file has to have the Julian date, flux of the target object, and the error of the flux. Once the file is uploaded on TAP a window will appear with the transit plot showing. Before the MCMC calculations of TAP are initiated, initial parameters must be set before processing the data. This analytic function requires the following parameters: planet orbit period P, planetary radius R_p, orbital semimajor axis a , stellar radius R_s, orbital inclination with respect to observer i, arguments of orbital eccentricity, e and ω, the time of transit center T_{mid}, and two parameters specifying a quadratic limb darkening law describing the occulted stellar disk [7]. The arguments of orbital eccentricity were locked since there was no interest in calculating them along with the Y-intercept of the airmass.

The MCMC technique allows for accurate calculation of probability distributions for model parameters [7]. Before the chain process was executed the number of max chains was set to one and the number of minimum links set to one thousand. The analysis was then initiated

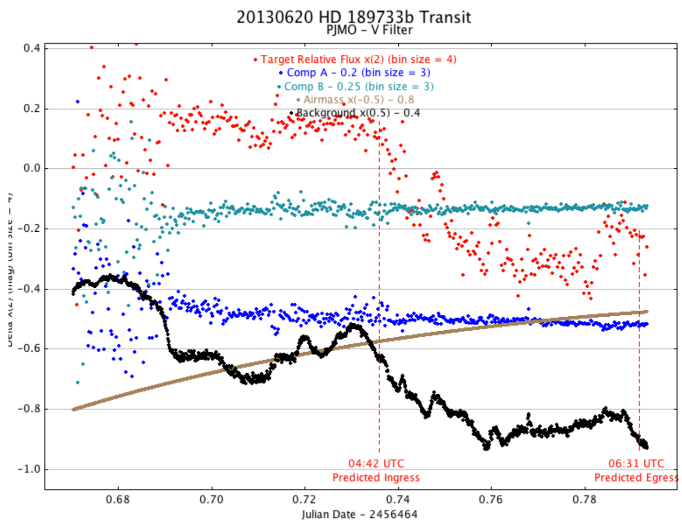

Figure 4: The plot above shows the lightcurve of the first observation the HD 189733b transit. Although the entire transit was capture the egress is absent. The red curve indicates the transit depth whereas the blue and dark green plots are the comparator stars. The brown curve is the air mass and the black curve is the background.

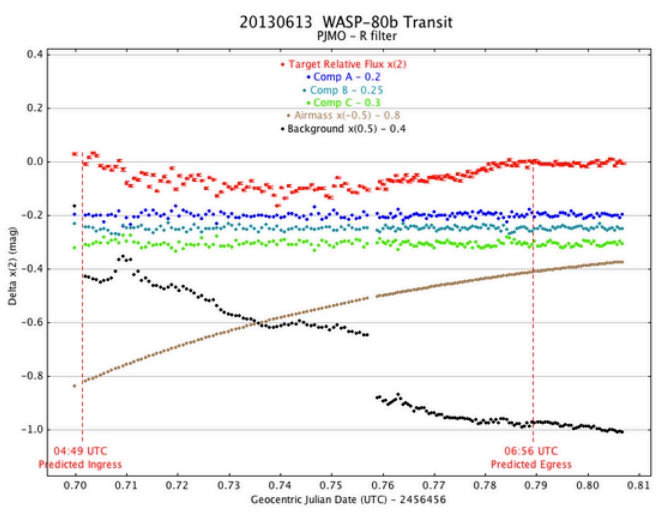

Figure 3: The plot above shows the lightcurve plot of WASP-80b.This was the only viewing of this transit. More than half an hour was captured after egress. The red curve indicates the transit depth whereas the blue, dark and light green plots are the comparator stars. The brown curve is the air mass and the black curve is the background.

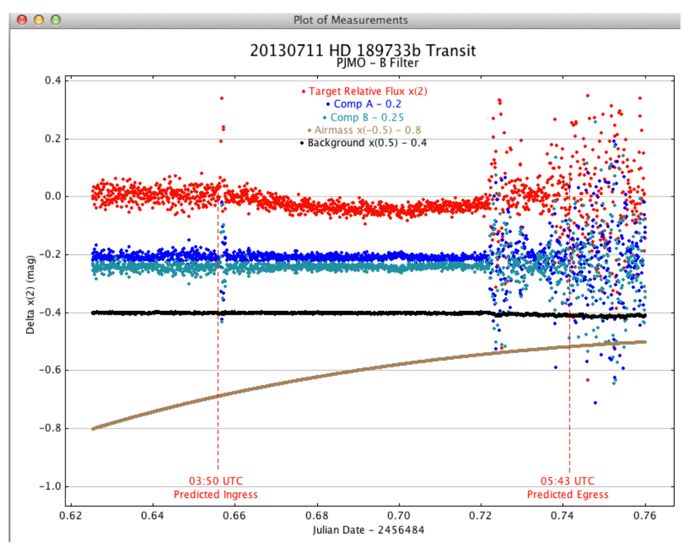

Figure 5: The plot above shows the second viewing of the HD 189733b transit. There was success in capturing the entire transit however there is a lot of noise at egress. The red curve indicates the transit depth whereas the blue and dark green plots are the comparator stars. The brown curve is the air mass and the black curve is the background.

V. Results

The calculated data on the extrasolar planet from both transits plotted of HD 189733b were compared to other published results. The processed lightcurve fitting of WASP-80b is also given in this section. TAP has generated the necessary results on the stellar radius of the planet along with the orbital period. The calculated results from TAP will be confirmed with the results from the exoplanet catalogue measurements of WASP-80b [6].

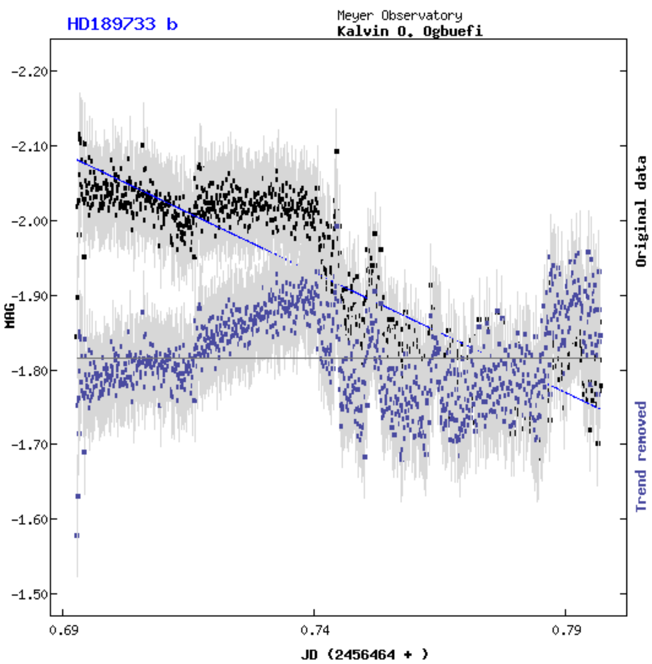

Figure 6: The fitted lightcurve above is from the first observation of HD 189733b. Since the egress was missing, the online fitting tool applied trend subtraction to the curve, which subtracted part of the curve to estimate the shape of the transit.

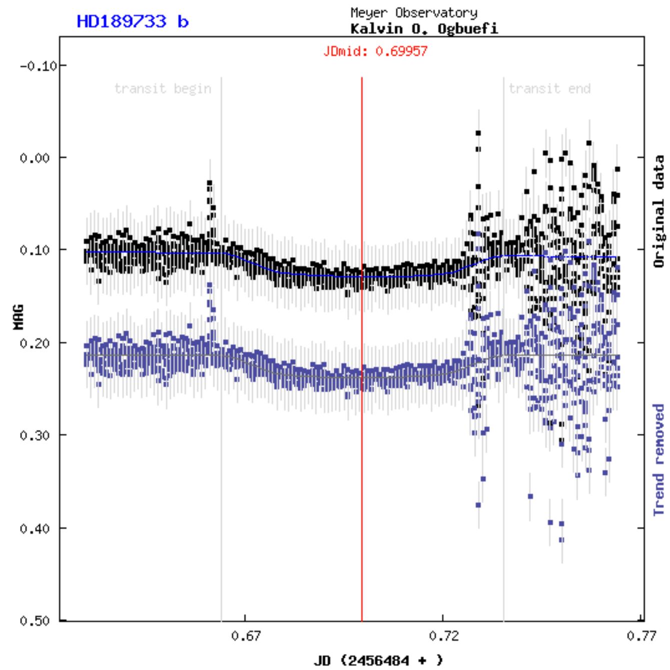

Figure 7: This is the second observation of HD 189733b.The fitted curve is much smoother than the first observation except for the noise at the end of the run.

	Catalogue data	Measured data
R_p:	1.138 +/- 0.027 R_{Jup}	**1.137** $_{-0.038}^{+0.037}$ R_{Jup}
R_*:	0.788 +/- 0.051 R_{Sun}	*fixed, errors included in i*
A:	0.03099 +/- 0.00063 AU	*fixed, errors included in i*
Per:	2.2185733 days	*fixed*
i :	85.76 +/- 0.29 °	**84.76** $_{-0.30\|1.14}^{+0.33\|1.32}$ °

Figure 8: The chart above displays the results that were extracted from the submitted data. The left side of the chart shows the catalogue measurements of the HD 189733b transit and the right shows the results.

The measured data from Figure 8 reveal that the radius of HD 189733b is 13.7% bigger than the radius of Jupiter compared to the catalogue data showing it to be 13.8% bigger. The results for the measured inclination angle show it to be 84.76 degrees compared to the catalogued inclination of 85.76 degrees.

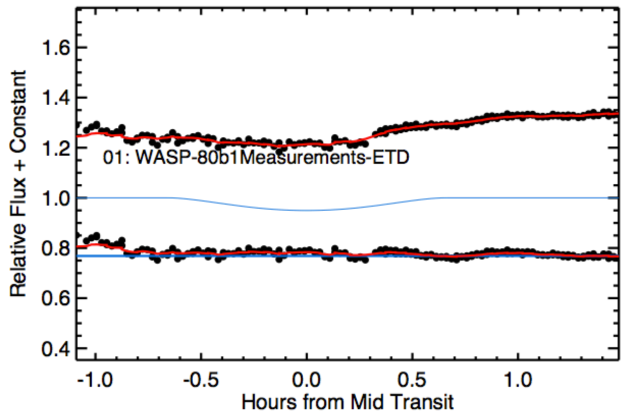

Figure 9: The plot above shows the result of the lightcurve fitting implemented on the WASP-80b data by TAP on IDL. The plot above the blue curve is the actual transit and the red curve is the fit. The black plot below the blue curve is the trend, which was subtracted from the transit plot.

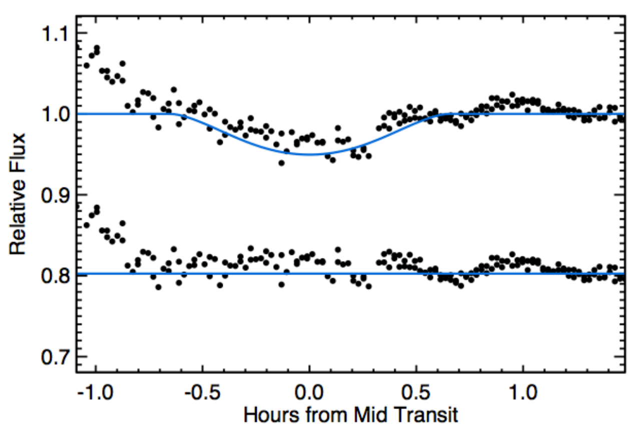

Figure 10: The plot above shows another fitting analysis TAP did with the lightcurve plot. TAP fitted a blue curve to the first plot to show the path of the transit whereas the blue curve goes right through the bottom of the plot below.

The orbital period that was calculated through TAP was 2.82 days whereas the documented period of WASP-80 is 3.06 days [6]. The other piece of information TAP calculated was the stellar radius of the planet. The value TAP calculated was .254 and the documented size is .168 showing a dramatic difference.

VI. Summary & Conclusion

The measured data from Figure 8 are within accepted values of the catalogue data from the lightcurve fitting tool on the exoplanet database. Although being a percent measurement away from both the catalogue values of the exoplanet radius and the angle of inclination the exoplanet database has proven to be an excellent resource in data analysis.

The comparisons with the calculated results on TAP and the documentation on the open catalogue for WASP-80b reveal a different story however. Resorting to IDL gave the opportunity to examine what the possible planetary parameters were along with comparing it to the documented parameters on the open catalogue for exoplanets. The stellar radius of the planet shows the most contrast as the calculated output from TAP was .254 and the documented value was .168. The fact that the orbital periods were relatively close in value yet the stellar radii weren't reveal that more data has to be collected and analyzed on WASP-80b.

This summer we were successful in collecting data on exoplanets WASP-80b and HD 189733b. We were able to extract the stellar info of both planets through the lightcurve fitting database website along with the transit analysis package, TAP, on IDL. This summer marks the first use of IDL software in the Baylor REU programs.

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