A Thesis Presented to

The Faculty of Alfred University

Stull Observatory Exoplanet Transits

By

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In Partial Fulfillment of
the Requirements for
The Alfred University Honors Program

April 2017

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1. Introduction

Is there other life in the Universe? This is arguably one of the most important questions for humanity. The search for life beyond Earth has inspired research for hundreds of years. In order to search for life, we must look to the places that could harbor it, exoplanets. Exoplanet is an abbreviation for the term Extrasolar Planets, meaning planets around stars other than our Sun. Exoplanets have been studied since the first confirmed discovery in 1992 (NASA, 2017). Over the past 25 years our understanding of life outside the Solar System has grown exponentially.

Since 1992 we have discovered 3,472 exoplanets (NASA, 2017). These planets can be discovered using a variety of methods, the most common being transits, radial velocity, imaging, and microlensing. Observing transits is the most significant method for detecting exoplanets. An exoplanetary transit is observed when the planet passes in front of its host star causing the light from the star to dim. In a star system, it is obvious that the planets revolve around their host star but it is not commonly known that the planets also cause the host star to wobble. This movement in the host star is small, but the velocity measured can be used to calculate the mass of the planet orbiting it, this is known as the radial velocity. Imaging simply involves directly imaging a planetary system by blocking the overpowering light from the host star. Microlensing is the process of measuring light bending from the host star due to gravity as the planet passes in front of it. Although there are alternative methods of detection these are the most important.

Discovery of exoplanets is not only helpful in our search for life but also in better understanding our own Solar System. We have encountered various types of planets, many that cannot be found locally. Terrestrial planets are classified as smaller, rocky planets often found closer to the host star (i.e. Mercury, Venus, Earth, and Mars). Jovian planets are gas giants that are known to form in the outer parts of the solar system (i.e. Jupiter, Saturn, Uranus, and Neptune). Some planet types found outside our Solar System include Hot Jupiters, Super Earths, and Cthonian Planets. Hot Jupiters are Jovian planets that have formed in the outer reaches of their system and migrated inwards towards the host star; they are the most commonly discovered exoplanet. Super Earths are planets that fall in size between Terrestrial and Jovian planets. Cthonian planets are believed to have formed as gas giants and as they migrate towards their host star their atmosphere is blown away leaving only the rocky core. The discovery of these various planets has allowed us to more accurately classify our own planets.

It is remarkable the amount of information that we can obtain from observing a transit. How often a transit occurs can tell us the orbital period which provides us with the distance between the planet and the star if the mass of the star is known. The mass of the star can be obtained once we measure its magnitude and distance. The depth of a transit relates the radius of the planet compared to its host star. In order to find the radius of the host star we use its luminosity and temperature which can also be calculated from its distance and magnitude. The age of the star can be determined from its mass and luminosity. Lastly, the orbital period and radius will tell us the velocity of the planet. Measuring the mass of a planet requires radial velocity measurements. Once the mass is obtained we can calculate the density of the planet. For comparison purposes mass and radius are measured in terms of Earth or Jupiter properties. Each of these characteristics are necessary for us to accurately classify an exoplanet.

The planet that we chose to observe is WASP-12b. Its existence was confirmed in 2008 (Hebb, L., 2009). With an extremely short period and unusually large radius, WASP-12b is classified as a Hot Jupiter. The frequency of its transits along with their depth make this planet an optimal target for observing. Due to this accessibility, there have been numerous observations of WASP-12b over the past 9 years. Its parameters are reported with extreme accuracy. The stellar and planetary properties can be viewed in **Table-1**.

The measurements for WASP-12b have been made from transit data and radial velocity measurements. The confirmed discovery of WASP-12b in 2008 came from the SuperWASP program of the United Kingdom (Hebb, L., 2009). Following the announcement of this extreme planet many astronomers were eager to observe it. This abundant collection of data allows the NASA Exoplanet Archive to constantly refine their parameters for WASP-12b (NASA, 2017).

Exoplanet observation is an emerging field in astronomy. It requires precision that is unavailable with most telescopes. Stull Observatory is home to four outstanding telescopes, both manual and automated. Viewing exoplanets opens a door for future students and researchers at Stull Observatory to continue doing so. Once we understand

Parameter	Symbol	Value	Units
Mass	M_p	$1.460^{+0.075}_{-0.068}$	M_J
Orbital Period	P	$1.09142030 \pm 0.00000014$	Days
Radius	R_p	$1.900^{+0.057}_{-0.055}$	R_J
Semi-Major Axis	a	$0.02340^{+0.00056}_{-0.00050}$	AU
Transit Duration	τ	2.9959 ± 0.0106	Hours
Temperature*	T_{eq}	2580^{+58}_{-62}	K
Density	ρ_p	$0.266^{+0.015}_{-0.014}$	g/cm^3
Transit Depth**	δ	15.1	mmag
Velocity	v	234 ± 9	km/s

Table-1a. WASP-12b Properties (Data from the NASA Exoplanet Archive). *Planetary temperature is calculated using spectroscopic data of the planet's atmosphere as well as the distance to its star.** Transit depth value taken from Exoplanet Transit Database.

Mass	M_*	$1.434^{+0.110}_{-0.090}$	M_{Sun}
Radius	R_*	$1.657^{+0.046}_{-0.044}$	R_{Sun}
Spectral Type	_____	G0	_____
Apparent Magnitude	m_V	11.69 ± 0.08	_____
Age	_____	2 ± 1	Gyr
Distance	d	427 ± 90	Parsecs
Right Ascension	RA	06h 30m 32.7s	_____
Declination	Dec	+29˚ 40m 20.2s	_____

Table-1b. WASP-12 Properties (Data from the NASA Exoplanet Archive)

the precision and capability of our telescopes, further research can be conducted. The goal of this research is to obtain a transit and compare our data to the existing data.

2. Procedure

Observing a transit requires that all conditions be perfect. Data collection must be timed with the transit. Along with finding a transit that occurs at night we must also coordinate with the weather. Exoplanet photometry requires clear skies with outstanding seeing conditions. Aligning the transit with the weather took us around two months.

On Monday February 27th, 2017, we were able to observe a transit for WASP-12b. The Austin-Fellows, a 32-inch Newtonian Reflector, was used for these observations. It was built in 1992 by Dr. John Stull, a Physics professor at Alfred University. It is completely automated using a CCD camera for imaging.

The night was clear through most of the observations. There were inconsistencies with the dome tracking in the Austin-Fellows. This required that I manually move the dome throughout the night. My observations began at 1:50(UT) and concluded at 4:55(UT) due to thicker haze rolling in and complications with the dome. Over this period I obtained 440 observations with an exposure time of 12 seconds in a clear filter. The star field can be viewed in **Appendix-A**.

We used IDL to perform photometry on the images. Two non-variable comparison stars were used for differential CKV photometry. The comparison stars were chosen for proximity and comparable magnitude to WASP-12, they are highlighted in **Appendix-B**. After conducting error analysis, the aperture with the least error for the target star was chosen to be 5 pixels. The images were bias subtracted and flat field corrected prior to photometry. We chose to neglect the dark correction as it only increased the error in our measurements. The differential photometry process zeroes the comparison star and shows the change in magnitude of the variable star. The check star is used to further reduce error in our measurements. This process is necessary because it removes any false variation that may be due to weather conditions or inconsistencies in the frame. In our case this change in magnitude measured is the transit.

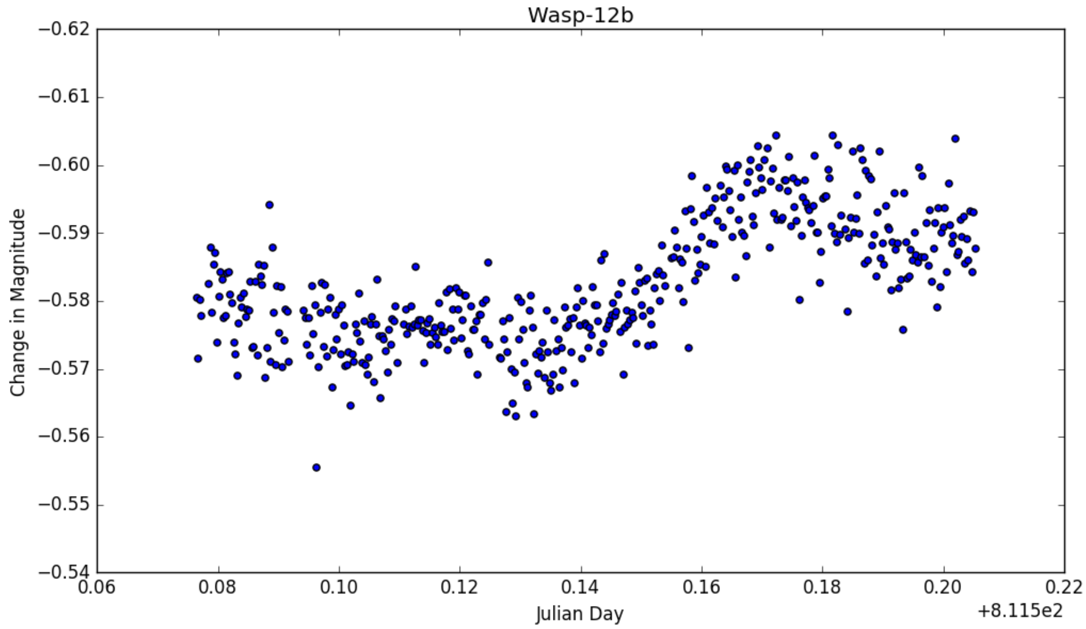


Figure-1. Wasp-12b Light Curve.

3. Results

Our light curve can be viewed in **Figure-1**. We took an average of the magnitude during the transit and an average of the magnitude out of transit and found a depth of $\delta = 15.8 \pm 0.6$ mmag. From this depth, we can calculate the ratio of the planet and star radii with the equation:

$$1 - 10^{-\delta/2.5} = \frac{{R_p}^2}{{R_*}^2}$$

Using the radius of WASP-12 given by the NASA Exoplanet Database we obtain $R_p = 1.84 \pm 0.12\ R_J$. From this radius, we can obtain the volume of the planet using the equation:

$$V = \frac{4}{3}\pi {R_p}^3$$

Parameter	Accepted Value	Measured Value	Units
δ	15.1	15.8 ± 0.6	mmag
R_p	$1.900^{+0.057}_{-0.055}$	1.84 ± 0.12	R_J
ρ_p	$0.266^{+0.015}_{-0.014}$	0.278 ± 0.057	$g/_{cm^3}$

Table-2. Accepted and Measured parameters for WASP-12b with error.

We get that $V = 9.50 \pm 1.92 \times 10^{24}\ m^3$. This will provide us with the density by using the given mass of WASP-12b provided by the NASA Exoplanet Database. The density is given by:

$$\rho_p = \frac{m_p}{V}$$

This gives us a density of $\rho_p = 0.278 \pm 0.057\ g/_{cm^3}$. We can now compare these values to the given values for WASP-12b.

We can also observe the time it takes for the planet to move from in transit to out of transit. This time change is related to the radius of the planet and the velocity by the equation:

$$t = \frac{2R_p}{v}$$

Using the given value of v from **Table-1a** we obtain $t = 1120 \pm 86\ s$. The difference between this time and the time measured from our light curve is given by $\Delta t = 750 \pm 300\ s$. This time difference tells us that it takes approximately 13 minutes longer than it would for a perfect sphere to make this transition. From this we can speculate that WASP-12b is a Cthonian planet. This slow time change may imply that we are seeing the atmosphere being blown away from the planet.

We can calculate an approximate difference in the calculated and measured radii from Δt. We get that $\Delta R = 1.2 \pm 0.5\ R_J$ which tells us that the atmospheric trail of the planet could be the size of Jupiter. In order to further analyze this planet, we would require spectral analysis and radial velocity measurements.

4. Conclusion

It is clear from our data that we did in fact observe the transit of WASP-12b crossing in front of its host star. Most of our values fall close to or in the range of error from the given value. These comparisons can be seen in **Table-2**. Our transit depth falls just outside of our calculated error. This error is highly affected by the photometry process therefore a different approach may have put this value within the error range. The radius and density of our planet do however fall within the allotted error of the accepted value. Therefore, our values coincide with the NASA Exoplanet Database values.

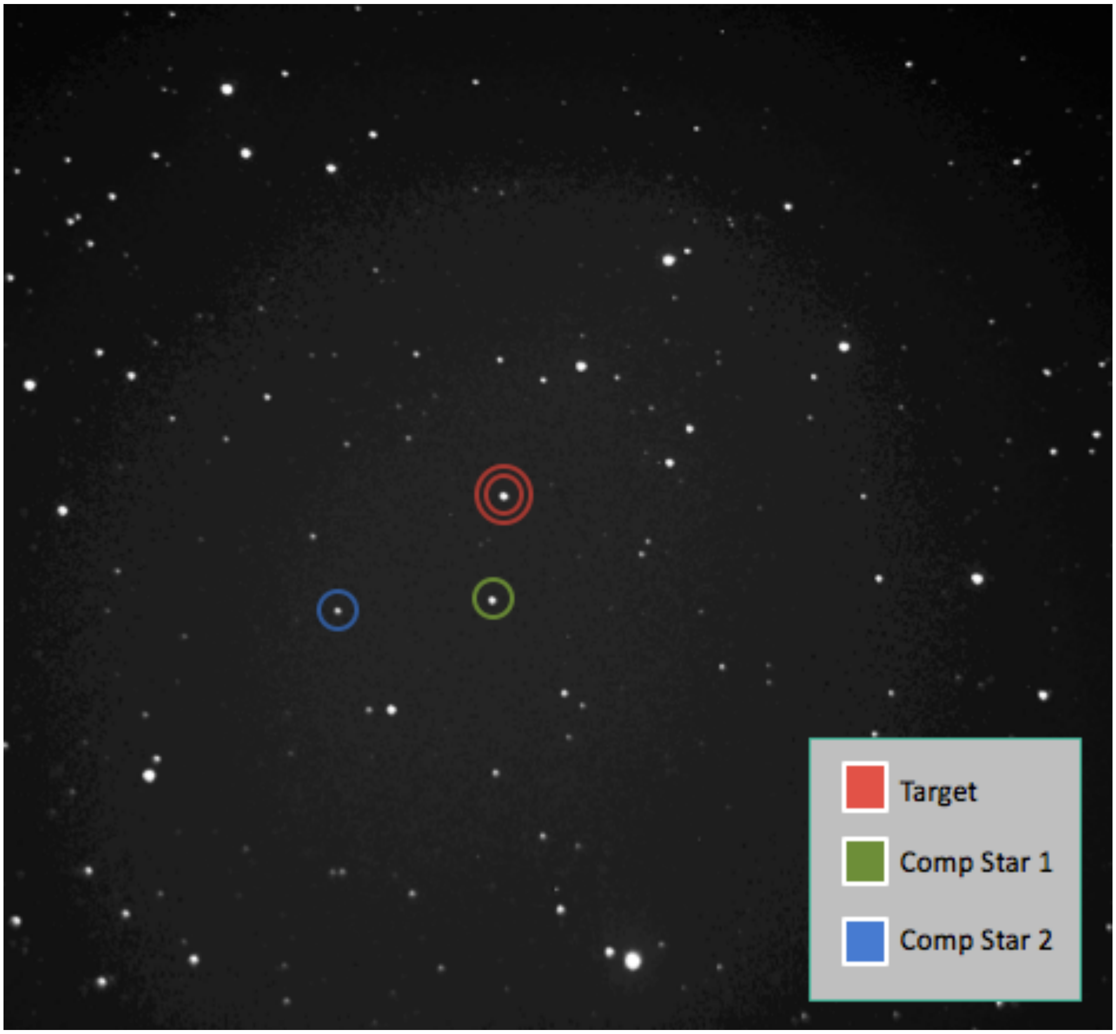
With these values, we can now classify the planet. Given the size of this planet it must be a Jovian. We can support this with the low density which implies that the planet is mostly made up of gaseous materials. Thus, knowing it has a short orbital period, our data agrees that this planet is a Hot Jupiter. We also gave evidence to show that this planet is most likely a Cthonian planet with its atmosphere being blown off.

From this data, we can conclude that the Austin Fellows telescope is capable of accurately measuring an exoplanet transit. This data and procedure can be used in future research at Stull Observatory. The research of exoplanets grows more important with time. As they are discovered researchers require ground-based follow up observations to refine the parameters of these planets. This data from hundreds of ground observatories gives us an accurate representation of these distant worlds.

Classifying planets like WASP-12b and learning more about them has allowed us to better understand our own solar system. We can question why these planets exist in other systems and not in our own. This all leads up to how Earth-like planets form and where we might find them. Finding a planet to support life outside our solar system is the ultimate goal for any exoplanet research team.

5. Appendices

Appendix-A. Star field of WASP-12.



Appendix-B. Star field of WASP-12 with comparison and target stars highlighted.

Citations

ETD – Exoplanet Transit Database. Czech Astronomical Society, n.d. Web. 14 Apr. 2017.

Hebb, L., A. Collier-Cameron, et al. "WASP-12b: THE HOTTEST TRANSITING EXTRASOLAR PLANET YET DISCOVERED." *The Astrophysical Journal* 693.2 (2009): 1920-928. Web.

NASA Exoplanet Archive. California Institute of Technology, n.d. Web. 14 Apr. 2017.