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Analysis of the Exoplanet HD 189733b to Confirm its Existence

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SUMMARY

In this study, we examined the orbital periods, photometry, and radial velocity of one exoplanet in the HD star system: 189733 b. We constructed a high caliber exoplanet transit detection tracker that acts as a means to analyze the data constituted of the Raw Science images that we obtained from a DSLR camera. We used the BATMAN Python programming package to convert our data to light curves and a radial-velocity model. The radial velocity data was taken from multiple high precision research studies, which were then converted to a sinusoidal graph portraying the radial velocity with respect to time. Chi-square tests were performed on the data in order to examine the likelihood that observation was due to mere chance. We hypothesized that the creation of a DSLR camera star tracker would produce results that support previously established studies. The results of our studies were statistically significant and supported our hypothesis and previous studies. This study demonstrates the importance of accurately using the radial velocity and photometry data from high-precision research studies.

INTRODUCTION

Exoplanets are planets that orbit stars other than the Sun (1). In this study, we aimed to detect exoplanets around the HD 189733 b star system using the transit method of planet detection. We built upon an existing methodology that will make exoplanet detection easier and much more efficient for astronomers. By doing so, we can exponentially increase the rate at which we discover exoplanets and make it much faster and simpler. By making equipment that is fast, economical, and usable, civilian scientists will also be able to access this technology. This would not only make exoplanet detection far faster but would also result in increased engagement with exoplanetary science for people of all ages.

The technology we employ is known as a barn door model star tracker. A barn door star tracker is an economical exoplanet detector that relies on an Arduino Uno and a bipolar stepper motor to control the platform where a camera rests. Between these two platforms there is a threaded rod that is spun by the motor. Additionally, using the Arduino IDE software application, we are able to program the motor to move at an identical rate that opposes the rotation of the Earth, resulting in a raw image without motion blur.

Here, we show that the barn door star tracker produces results remarkably similar to advanced space and ground based telescopes, such as the Hubble Space Telescope, Kepler Space telescope, or the Gemini Planet Imager. These research surveys of our universe require significant expertise to operate and use, which make these methods of exoplanet detection out of reach for aspiring scientists and the general populace. Even though these telescopes undoubtedly have better quality and pictures, we hypothesized that our star tracker would produce transit curves similar to those of professional scientific research studies.

Many detection methods for exoplanets exist (2), but the one that has been used most frequently by astronomers and physicists is “the radial velocity method” (3). The radial velocity method relies on detecting the “wobble” of a star, i.e. the movement of a star as it revolves around a center of mass, as a result of the gravitational attraction between the exoplanet and the star. If the radial velocity is cyclical, there is evidence that an unseen planetary companion exists in orbit around the star.

Even though the radial velocity method (4) has been used to detect a vast majority of exoplanets, recently, however, the photometric analysis method has become increasingly useful for the same purpose. Photometry helps scientists discover exoplanets through the obstruction of light by the host star of an exoplanet. Because of this small dip in the measured light intensity, we can then convert this data to a light curve graph. If the resulting curve is cyclical, we can conclude that there is an unknown planetary companion (or orbital body) in orbit around the star of significance. Here, our study was able to analyze and confirm the existence of an already existing extrasolar planet (5) with results similar to the ones acquired from a previous study on the HD 189733 star system. One of the most important steps to our project was to measure the planet’s orbital period through the use of Kepler’s third law (6) and to measure the length of the planetary axis.

Since the exoplanet that we observed has a small orbital radius and a relatively large mass compared to other planets, it has a short orbital period. These planets are known as “Hot Jupiters.” By examining this hot Jupiter, we found that the results -- collected through the observation of an exoplanet in transit around a star using a DSLR camera -- is in direct correlation to a previously conducted study. The results of our study very closely mirror the result of the previous study.

We hypothesized that our development of a star tracker

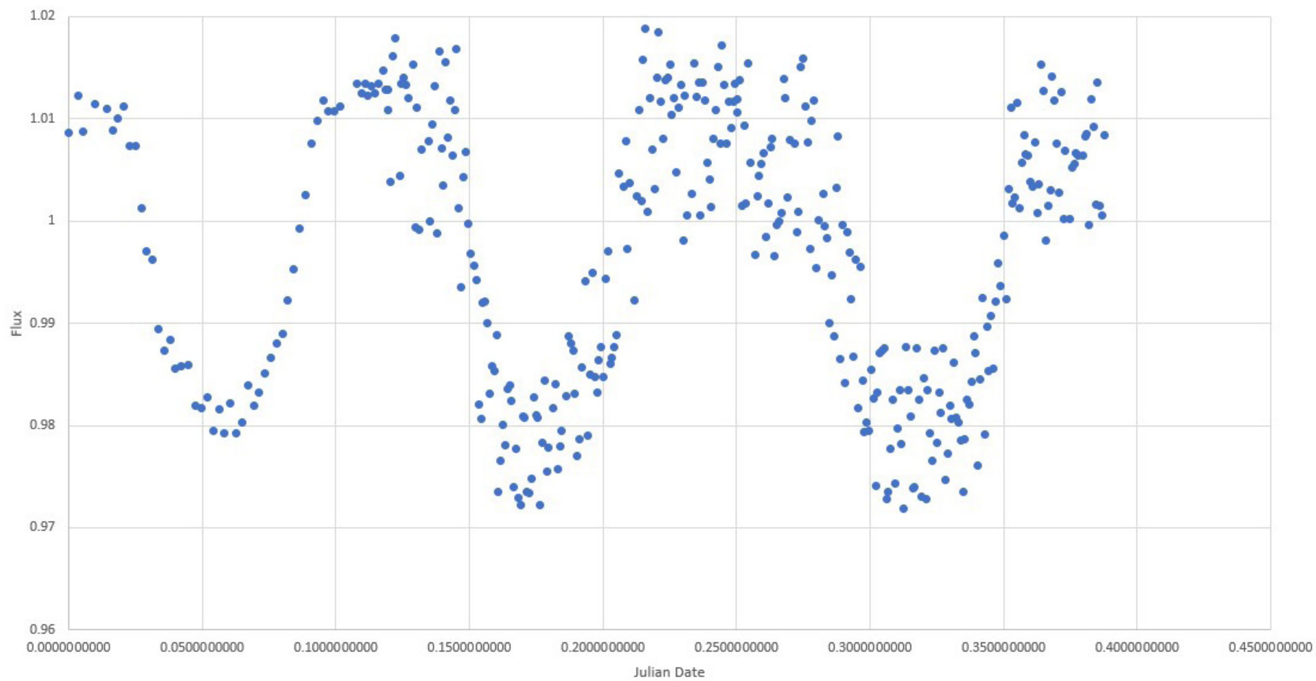

Figure 1. Shows the photometric/light curve of HD 189733b from our first field observation. The cyclical nature of this graph shows that there is indeed an exoplanet that orbits the star. Julian time was converted such that the first value was zero. The succeeding values represent the difference between the current and preceding Julian Time values.

will have similar results to that of the modern exoplanetology technology. The results of our studies were statistically significant, so it supported both our hypothesis and previous studies on the subject. Our study was able to confirm the feasibility of detecting exoplanets by using a far more economical method that produced almost the same results as other studies (7).

This work may help increase the rate at which new exoplanets are found and therefore will help astronomers and physicists discover new worlds that may even be habitable (8) and ready for future colonization by humanity. Furthermore, by learning about exoplanets, we can learn about Earth (and humanity's) place in the universe.

RESULTS

We found that it is feasible to detect exoplanets using inexpensive and readily available technology.

Therefore, our studies show that it is possible for exoplanets within 100 light years from earth to be detected using a barn door star tracker. The radial velocity (4) and photometric analysis surveys that we conducted on the exoplanets supported the existence of hot Jupiters. The data presented here produced a cyclical photometry graph in agreement with the results of previous studies.

Light-Curve Analysis

We began by calculating the radius of the planet. The photometry light curves for HD 189733 b were normalized to a baseline value of 1.0 in order to make the data more readable and understandable. The star in consideration is a K-type star, which implies that it has a solar radius of between 0.7 - 0.96. **Equation 1** describes the relationship between the ratio of the flux change, ΔF, to normalized flux, F, and the radius of the planet squared, $R^2{}_p$, to the radius of the star squared, $R^2{}_s$, from the point of view of the observer.

Equation 1: $$\Delta F / F = R^2{}_p / R^2{}_s$$

Our results support our initial hypothesis as they not only agree with some of the results of a previous study (9), but also shows our predicted photometry and radial velocity curves were accurate (**Figure 1**). We used a Chi Squared (χ2) test on the data that we gathered. We found that the results of the test were statistically significant and showed a similarity with previous literature values.

Chi-Squared Results

The values in the flux graph indicates that there is an exoplanet around the star we were observing. This is because the exoplanet produced a light curve that was cyclical in nature. Our null hypothesis is that H_0: μ = 1, which implies that there is no exoplanet because of a uniform distribution of points. Our alternative hypothesis was that H_A: μ ≠ 1, which suggests that the values do not always center one, and instead, they fluctuate.

The null hypothesis simply states that the values center around a range of values close to one, which would indicate that the exoplanet was transiting around a star. The alternate

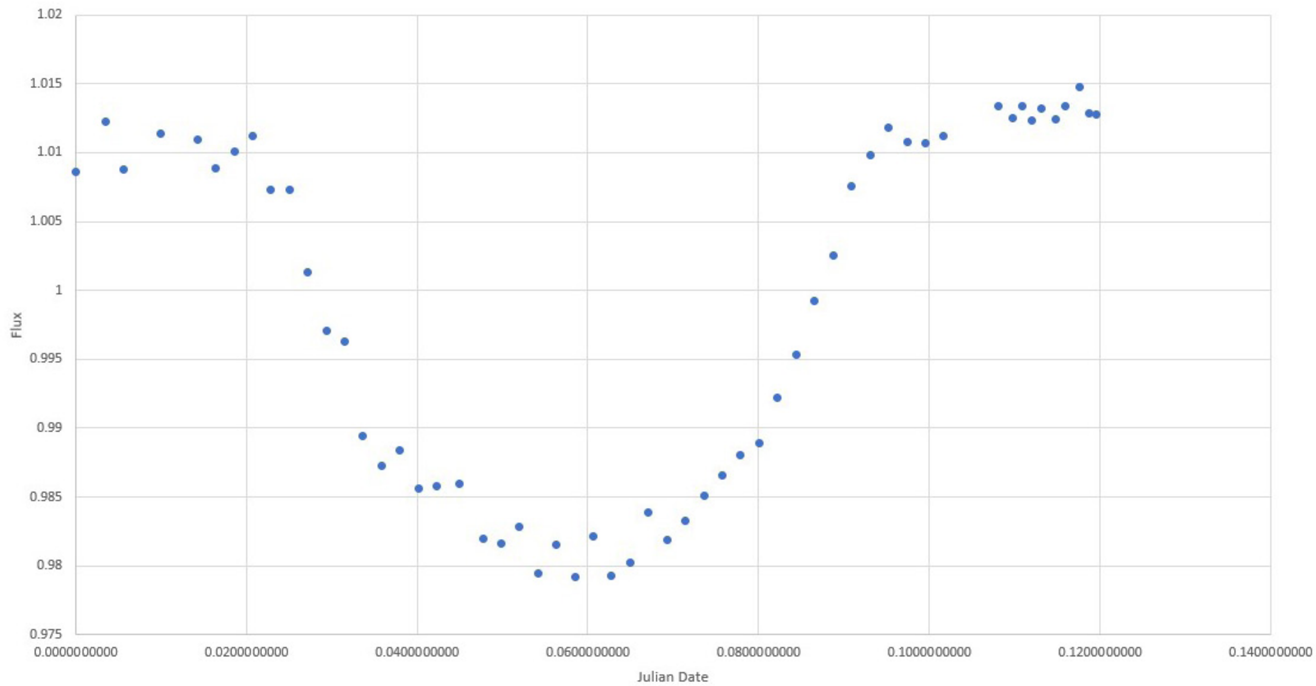

Figure 2. This is the second field observation of the exoplanet. Once again, the graph is shown to be cyclical in nature. Therefore, both of our field observations show that there is an exoplanet in existence.

hypothesis states that the exoplanet would not center around a mean value of one and would not indicate the existence of an exoplanet.

The $\chi 2$ statistic was approximately 22352. The degrees of freedom that we used was 372 (as there were 373 categories). The *p*-value that was calculated was less than 0.05, so we supported our alternative hypothesis and rejected the null hypothesis. This supported our original hypothesis.

DISCUSSION

In this study, we did detect a statistically significant shift in the images obtained by our barn door star tracker. This supported previous studies on the same exoplanet.

This new method will be helpful in discovering more yet unknown exoplanets and show that many studies on exoplanetology must be revamped with the new methods and tools at our disposal. The results that we acquired show the immense importance of updating information about planetary bodies and to actively change information based on new results and discoveries.

A shift in the orbital radius of the planet from when it was last discovered shows that there is a statistically significant shift with the flux change of the exoplanet. This is primarily because of Kepler's third law (**Equation 2**), which describes a proportional relationship between the square of the orbital period (T) and the cube of the semi-major axis (a) (10).

Equation 2: $$T^2 \propto a^3$$

Because the barn door star tracker that we used to obtain these results was not as sophisticated as professional star trackers, we were limited in the range of opportunities we had to discover and track exoplanets. The main exoplanets that we tracked were ones that were less than 100 light years from the earth.

The technology we had at our disposal made it nearly impossible for us to track and analyze exoplanets which were a significant distance away from our position. We believe that this is one significant drawback of this approach to discover new exoplanets.

Furthermore, the results that we obtained were primarily used to demonstrate the feasibility of using technology that is less advanced than professional telescopes, star trackers, and spectrometers at professional universities, laboratories, and observatories. Great emphasis must be put on the fact that our star tracker does not serve as a replacement of professional star tracker, but rather as a supplement to aid and accelerate the pace at which we detect more exoplanets.

The star tracker technology that we advocate will help civilian scientists help far more in the discovery of exoplanets. We firmly believe that incorporating this star tracker as a lab instrument will greatly help with the discovery of new exoplanets and will help both professional and amateur scientists discover more about the universe.

METHODS

We focused primarily on the transit method (photometric analysis). The transit method is used to observe the shift in brightness as the exoplanet orbits around the star, and radial velocity is observed as the change in frequency (11) caused

Amateur Star Tracker	Professional Star Tracker
The photometric curve produced by a custom made star tracker closely mirrored the one in a previous research study.	Professional telescopes and star trackers can create photometric curves of even dim stars.
Custom star-trackers can only produce the photometric curve of highly visible stars such as the HD star system.	Professional telescopes can detect the radial velocity of any star.
Homemade star trackers cannot plot the radial velocity graph of a star.	Observatory telescopes can easily detect any anomaly in the data and relay it to a team of professionals.

Table 1. Depicts key differences between our amateur star tracker and a professional star tracker. Although our star tracker is more economical, it lacks some of the sophisticated machinery possessed by professional ones. However, ours is able to be used when exoplanets are 100 light years from the earth or less.

by stellar "wobble."

Data Collection

We gathered data through the creation of a star tracker, built using an Arduino microcontroller, stepper motors, and 3D printed parts. The star tracker was created to gain accurate data, enabling us to follow the star and counteract the rotation of the earth. We determined that the tracker needs to move approximately 0.25 degrees per minute, so to accurately move the star tracker, we used bipolar stepper motors and a screw/gear system. In the Arduino programming language, we initialized the ports to specific coils in the stepper motor and set the speed to move at the rate stated previously. Then, we used a Canon DSLR camera with a ball-socket mount and attached it in the center of the apparatus to acquire images. The main reason for following the star was to acquire the flat, dark, and biased frames that were then calibrated.

Data Calibration

We then calibrated our data to acquire the flat, dark, and biased images. A flat image is a frame that determines the correction factor when pixels are exposed to the same amount of light. To acquire this image, we applied a uniformly even source of light with normal exposure time and capture the image. A bias image is a frame, captured with short exposure time and with the camera lens attached, that determines the amount of noise in a camera. This inherent noise is caused by the accumulated electron frequency of the Charged-Coupled Detector (CCD) chip. A dark image is a frame that contains this "bias" and is removed to correct the image to get a pure, dark image. From these frames, we created MasterDark, MasterFlat, and MasterBias images. These master frames were processed through a python program that stacked and averaged all of the images to create an accurate, unbiased image(with the formula below) to be analyzed through AstroImageJ.

The star tracker was calibrated to point towards the star (and exoplanet) that was being observed. A particular date from the exoplanet transit database (12) was picked in order to pick the most opportune time to detect the exoplanet. The star tracker was calibrated to take astronomical photographs every 30 seconds during the entire period of the transit. The image frames were then stacked on an exoplanet imaging software known as SharpCap to be able to compare the values. The result was the exoplanet transit curve.

Data Analysis/Confirmation

We used AstroImageJ to process the data. AstroImageJ is a data imaging graphical user interface that reduces and simplifies the data to create a photometric light curve. To create this light curve, AstroImageJ picks a comparison star that does not contain an exoplanet and compares the change of flux (from a baseline value) in relation to comparable stars. We also conducted research on data previously collected by professional astronomers and physicists. We compared our data to this previously conducted research to ultimately validate our hypothesis.

The BATMAN python programming package was also used in order to generate a curve of best fit for the comparison graph that we generated (13).

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