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Measuring Exoplanet Radii: GJ-436b & WD 1856+534b

Alisha Choudhary,[1]
ASTR 510

[1] *San Diego State University*

ABSTRACT

On April 23, 2023 exoplanet transits of GJ-436b and WD 1856+534b were observed. The Mount Laguna Observatory 40-inch telescope was utilized to take photometric data of the transits. Both transits were observed in full, and a plotting software was used in order to model the transits' light curves. Prior published data and the transit's light curves were used to deduce the radii of both exoplanets. The radius of GJ 436b was found to be 0.31419 ± 0.01803 R_{J}. The radius of WD 1856+534b was found to be 0.92804 ± 0.03826 R_{J}.

1. INTRODUCTION

One of the most fruitful exoplanet detection methods is the transit method. This is when an exoplanet is observed transiting its host star, and the subsequent dimming of starlight can be used to calculate the radius of the exoplanet, using Equation 1.

$$R_p = R_* \sqrt{\delta} \qquad \text{[Equation 1]}$$

where R_p is the radius of planet, R_* is the radius of star, and δ is the transit depth.

The shape and depth of transit light curves is dependent on the wavelength in which they are observed. Transits are geometric effects with four contact points. First contact is when the planet's disk first touches the edge of the star, second contact is when the planet's disk fully covers the star, third contact is when the planet's disk begins to leave the star's disk, and fourth contact is when the planet's disk completely leaves the star's disk. Limb darkening is an optical effect that causes the edges of a star to be dimmer compared to the center of the star. Limb darkening is wavelength dependent and affects the curvature of transits. Transits are the most flat-bottomed and deeper for reddest wavelengths where limb darkening is weaker Haswell (2010). Flat-bottomed transits are preferred because they allow the second and third contact points of the transit to be clearly determined. Unlike other astronomers, exoplanet astronomers prefer a larger on-sky pixel sizes because this allows for a bigger field of view. This requires purposefully undersampling the point-spread function (PSF), which degrades photometric precision.

2. OBSERVATION

All data were acquired on April 23, 2023 using the 40-inch telescope at Mount Laguna Observatory (MLO). UT time was within a second of the GPS clock. The night was moonless and for the most part, cloudless. The transit ephemeris tool from NASA's Exoplanet Archive was used in order to select the targets observed this night Berriman et al. (2009). Both targets had low airmasses, and their ingresses began after twilight. The MLO 40-inch camera has an E2V 42-40 CCD with 2048x2048 pixels. The gain of the CCD is 2.13 and the readout noise is 3.88 electrons. Dark noise is negligible due to the liquid nitrogen that is used to cool the CCD. Since the data were binned 2x2, the pixel scale was 0.72"/pixel. All observations were carried out in the R-John band. 15 zero-second bias frames were taken with the shutter closed. 30 twilight flats were taken after this. Twilight ended at approximately 3:52 UTC.

2.1. *GJ-436b*

GJ-436 is an M dwarf star with an apparent magnitude of 10.7 located approximately 33 light-years away in the constellation of Leo. M dwarfs are especially good candidates for exoplanet transits for several reasons. They are the most common type of star by far. In addition, they have short orbital periods, and the longest lifetimes, and produce the deepest transits if the planet is around the same size as the star. All of these factors make exoplanet transits around M dwarfs easier to discover. A drawback to M dwarfs is their dimness. For GJ 436, this is not the case. GJ 436's transiting exoplanet is the warm Neptune-sized exoplanet, GJ 436b. GJ 436b has been theorized to be a prototype of similar planets whose late migration was caused by their outer companions Bourrier et al. (2022). GJ436b's transit was 45 minutes long, beginning at approximately 4:03 UTC. The event midpoint occurred at 4:23 UTC, and the event ended at 4:46 UTC. The expected transit depth was 0.689652%. The airmass hovered around 1 for the entire transit. We observed GJ 436b with 7-second exposures.

Several factors contributed to the non-uniform decline in sky brightness in Figure 1, which was expected to follow a smooth exponential decay. These included faulty telescope guiding, the inherent brightness of the host star, and fluctuation in the FWHM. After the 35th exposure, we noticed our target was not staying on the same pixels. This was due to the setting the group who had observed the night before had put in. The right ascension (RA) tracking rate of the telescope was running at 15.035, so we changed it to 15.045. Since GJ 436 was so bright, in order to not oversaturate the CCD, we had to constantly change the focus of the camera. The FWHM fluctuated between 2.5 to 3.3, which also required the focus to be changed since a larger PSF was desired. These factors all contributed to the data having a large scatter prior to ingress, as is apparent in Figure 2.

2.2. *WD 1856+534b*

WD 1856+534 is a white dwarf with an apparent magnitude of 15.429 located approximately 80 light-years away in the constellation Draco. WD 1856+534 is an approximately Jupiter-sized planet Vanderburg et al. (2020). WD 1856+534b's transit was only 8 minutes long, beginning at approximately 6:44 UTC. The event midpoint occurred at 6:50 UTC, and the event ended at 6:54 UTC. The expected transit depth was 56.65%. Due to the dimness of the white dwarf, longer exposures would have been preferred, but since the transit was so short, we decided to take 60-second exposures. This was done in order to make sure there were not only four data points. This transit was predicted to be so deep because the WD 1856+534b is much larger than the WD 1856+534b. This transit was also unique because of the inclination, which allowed for ≈ half of the starlight to be blocked. The airmass hovered around 2.2 during this transit.

3. DATA CALIBRATION

All data were processed using the open-source image processing program AstroImageJ (AIJ) Collins et al. (2017). AIJ was used to calibrate the data, produce light curves, and model the transits of the exoplanets.

To calibrate the data, all images had to be de-biased and flat fielded. The purpose of bias frames is to reduce readout noise. AIJ created a master bias frame from the 15 bias images. The master bias frame was subtracted from all the science frames to reduce noise. Flat fielding is done in order to account for pixel-to-pixel variation in the CCD. Similar to the master bias frame, AIJ constructed a master flat image from the 30 twilight flats. All images were divided by the master flat in order to normalize them. After debiasing and flat-fielding, AIJ's align stack tool was used in order to align the images. As mentioned earlier, there was an issue with the RA tracking with the telescope, so this step was necessary to complete before performing differential aperture photometry.

Differential aperture photometry is used to measure the brightness of a target by comparing it to nearby constant stars around it. The desired target's light curve is divided by the comparison stars' light curves in order to correct for atmospheric extinction. Apertures should be chosen to be large enough to capture most of the starlight whilst minimizing noise.

For GJ-436b, I attempted multiple apertures, ranging from 12-17 to determine the best transit curve. Since the data before transit had a lot of scatter, I first attempted to isolate the data points after egress which had less noise, and determine which aperture produced the lowest standard deviation. In doing this, I noticed a trend that smaller apertures produced lower standard deviations. However, this was not the case with the AIJ model fit. In AIJ, I selected five comparison stars for GJ 436. Two had to be thrown out because they exhibited sinusoidal behavior. Using the fit mode I entered in the period, host star parameters, and inclination [Table 1]. I found an aperture of 15 produced the lowest χ^2, a value of 8.68. This aperture's transit fit's RMS value was 4.88739. GJ 436's transit curve plotted alongside the comparison stars is in Figure 1. The transit fit with the parameters in Table 1 is in Figure 2.

For WD 1856+534b, I also attempted multiple apertures ranging from 10-15. I selected four comparison stars but had to throw one out because it exhibited a sinusoidal pattern. I used AIJ's model transit fit feature and entered values for the period, host star parameters, and inclination [Table 2]. An aperture of 10 produced

$T_{\rm eff}$	3586.10656 ± 36.36721 K
M_*	0.44117 ± 0.00939 $M_\odot$
R_*	0.41684 ± 0.00756$R_\odot$
i	$86.44^{+0.17}_{-0.16}$ °
P	2.64388 ± 0.00000 days

Table 1. GJ 436 Stellar Parameters

the lowest χ^2, a value of 1.32.

$T_{\rm eff}$	4710 ± 60 K
M_*	0.518 ± 0.0055 $M_\odot$
R_*	0.01310 ± 0.00054 $R_\odot$
i	88.778 ± 0.059 °
P	1.40794 ± 0.00000 days

Table 2. WD 1856+534 Stellar Parameters

4. RESULTS

For GJ-436b, I measured the transit depth to be 53.33 %. Using the published value for the radius of GJ-436b [Table 1] and Equation 1, I found the radius of GJ-436b to be 0.31419 ± 0.01803 $R_{\rm J}$. This is in close agreement with the published value of 0.372 ± 0.015 $R_{\rm J}$. For WD 1856+534b, I measured the transit depth to be 0.6%. Using the published value of WD 1856+534's radius [Table 2] and Equation 1, I found the radius of WD 1856+534b to be 0.92804 ± 0.03826 $R_{\rm J}$. This value is in very close agreement with the published value of 0.928 ± 0.089 $R_{\rm J}$.

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