Transit of Exoplanet K2-45 b

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Introduction

In this project, we observed the transit of exoplanet K2-45 b, analyzing the data we obtained from this transit.

K2-45 b is an ice giant exoplanet similar to Neptune. It is located about 1600 light-years away from Earth. K2-45 b was detected through the transit method by the K2 mission, which allowed for continued observations by the Kepler space telescope. Its discovery was announced in 2016.

The motivation for the project was to gain familiarity with the observation and data analysis processes in observational astronomy by obtaining a light curve for an exoplanet transit. Another motivation was to determine if the data we obtained and reduced for this exoplanet transit would be similar to data obtained by other researchers of the same exoplanet. In addition, we wanted to learn more about parameters that affect exoplanets and their importance in determining the characteristics of the exoplanet itself.

Observations

The observations were taken using the Mont4K CCD at the Steward Observatory 61" Kuiper Telescope on Mt. Bigelow, north of Tucson, Arizona. The Kuiper Telescope is at an elevation of 8235 feet, with an aperture of 1.54 meters, a focal length of 9.6 meters, and an equatorial mount with a limit of 65-degrees N. The Mont4K CCD is 4096 x 4097 pixels in size (15-micron pixels). It has an image scale of 0.14 arcseconds per pixel or 7.1 pixels per arcsecond. The field of view is 580 x 580 arcseconds squared, or 9.7 x 9.7 arcminutes square. The gain is 3.1 electrons per ADU, the readout noise is 5.0 electrons, and the dark current is 16.6

electrons per pixel per hour. The full well capacity is 131,000 electrons unbinned, or 191 Ke for 2x2 binned. The Mont4K CCD operates at a temperature of -130 degrees Celsius.

The observation period started at 11:55:24 PM local time on February 25, 2022. The observation period ended at 3:24:57 AM local time on February 26, 2022. The images were taken using an R band filter. The exposure time per image was 30 seconds. There were 314 images taken throughout the transit.

Data Analysis

Before obtaining the images for data analysis, our professor, Dr. Green, manually corrected for cosmic rays that were very close to or on the star K2-45 during the imaging. In addition, Dr. Green also corrected the bad columns of the CCD.

Using AstroImageJ software, a differential photometry process was completed. Before beginning photometry, a calibration process occurred. First, one image including a meteor trail was removed from the set to be used for the photometry, leaving 313 images for data analysis purposes. In addition to the images for the transit, the data also included a combined bias image and a combined normalized flat field image in the R filter. Using these images, bias subtraction and flat fielding were completed on the transit images. The calibrated images were saved in a new subdirectory for use in the differential photometry process.

For the differential photometry process, the Multi-Aperture Photometry tool within AstroImageJ was used. The calibrated images were loaded as an image sequence. We completed the differential photometry process with ten stars within our images. The aperture radius was 4.2 arcseconds. The inner radius of the background annulus was 7.56 arcseconds. The outer radius of the background annulus was 11.34 arcseconds. The target star, K2-45, was selected using the tool. After that, 9 more comparison stars were selected using the tool. These stars are indicated on the finder chart in Figure 5. A preliminary light curve for the transit of K2-45 b was obtained using the graph created of the flux of the target star versus time during the differential photometry process. A spreadsheet of values, including times, flux values for the target and comparison stars, error values for the flux measurements, and other important values, was created in the differential photometry process and was used in the data fitting process.

Data Fitting

To fit the data, we utilized a Jupyter notebook with the batman, NumPy, Matplotlib, SciPy, and Statistics packages. The batman package was created to model exoplanet transit light curves. First, we began by reading the time, the flux of the target star, and the error of the flux from the spreadsheet, storing them in lists. We then normalized the target star flux by dividing each flux value by the median of the flux values before and after the transit, when the flux values were relatively stable. Using code from the batman website, we created an object to store the various transit parameters and placed that object and the model initialization within a function. The four parameters we changed for the optimized model curve were the time of inferior conjunction, the radius of the planet in terms of stellar radii, the semi-major axis in units of stellar radii, and the orbital inclination in degrees. A guess parameters list was initialized with a time of inferior conjunction that was the median of the time data, and the planet radius, semi-major axis, and orbital inclination from the paper entitled *Characterizing K2 Candidate Planetary Systems Orbiting Low-mass Stars. II. Planetary Systems Observed During Campaigns 1-7* (Dressing et al. 2017). We accessed these latter three parameters through the NASA Exoplanet Archive. A scatter plot was created of the normalized flux versus the time. Then, on top of that, we overlayed two curves. The first was created using the parameters from the Dressing et al. paper from the guess parameters list. The second utilized the SciPy Optimize

Curve Fit function. Using this function, the parameters were all optimized to fit the data from the scatter plot in the best way.

The goodness of fit for the optimized model curve was determined by using the residuals. Figure 4 is a plot of the residuals, which are calculated by taking the observed flux of K2-45 and subtracting the modeled flux. The average of the residuals was calculated to be approximately 2.7065×10^{-5}, while the standard deviation of the residuals was calculated to be approximately 0.0036. For the optimized curve fit to be considered a good fit, the average of the residuals should be approximately zero. The optimized model curve is a good fit for the observational data because our value for the residuals is close to zero. In addition, the value for the standard deviation of the residuals should be approximately equal to the average of the errors on the data points. Initially, the average of the errors was not approximately equal to the value of the standard deviation of the residuals. To correct the error bars, the error was first normalized by dividing each of the individual data point errors by the mean of the errors. To obtain a list of the final errors, this normalized error was multiplied by the standard deviation of the residuals. The mean of this final error list was taken to obtain a scaled average of the errors. The scaled average of the errors was approximately 0.0036, which is also the approximate value of the standard deviation of the residuals.

Results

The results from our optimized curve fit are as follows. The time of inferior conjunction in units of JD – 2400000 was 59636.8596. The planet radius in terms of stellar radii was 0.137620201. The semi-major axis in units of stellar radii was 8.20559426. The orbital inclination in degrees was 87.4060374.

In order to better compare these values to the Dressing et al. paper and to radii within our Solar System, we converted the planet radius and semi-major axis to units of Jupiter radii and AU, respectively. The Dressing et al. paper has the planet radius as 0.9314 Jupiter radii, and it has the semi-major axis as 0.025 AU. Assuming a stellar radius in units of the Sun's radius of about 0.7, the curve fit planet radius is 0.959 Jupiter radii. Using the same stellar radius assumption, the curve fit semi-major axis is 0.0267 AU.

Discussion & Analysis

From these observations, we can determine the radius, semi-major axis, and orbital inclination of K2-45 b. We can use the radius to compare K2-45 b's size with the size of objects in our Solar System. Additionally, we can also combine this knowledge with the spectral type of K2-45, which is the K spectral type, to determine the habitable zone around the star and where K2-45 b is in relation to that zone using the semi-major axis. We can also determine the composition of the exoplanet based on where it is in relation to K2-45. Combining that with the radius, we may be able to achieve an estimate of K2-45 b's mass. From the orbital inclination, we can tell that the exoplanet was in a nearly edge-on orbit, enabling us to observe the transit from Earth.

Figure 3 shows the four parameters obtained from the curve fit of our data versus the parameters from the Dressing et al. paper. The parameters we obtained are very similar to the parameters in the paper. Figure 2 also demonstrates the similarity in the two models, with both overlayed on top of the scatter plot of our flux data from the transit.

Conclusion

Through this project, we observed and analyzed data for the transit of exoplanet K2-45 b. Through completing this project, we gained familiarity with the observing techniques and data analysis tools used in observational astronomy. We also obtained parameters for the planetary radius, semi-major axis, and orbital inclination of K2-45 b based on our model fit, which were similar to the parameters found in Dressing et al. We also obtained a model that fit the observed data well.

Figures

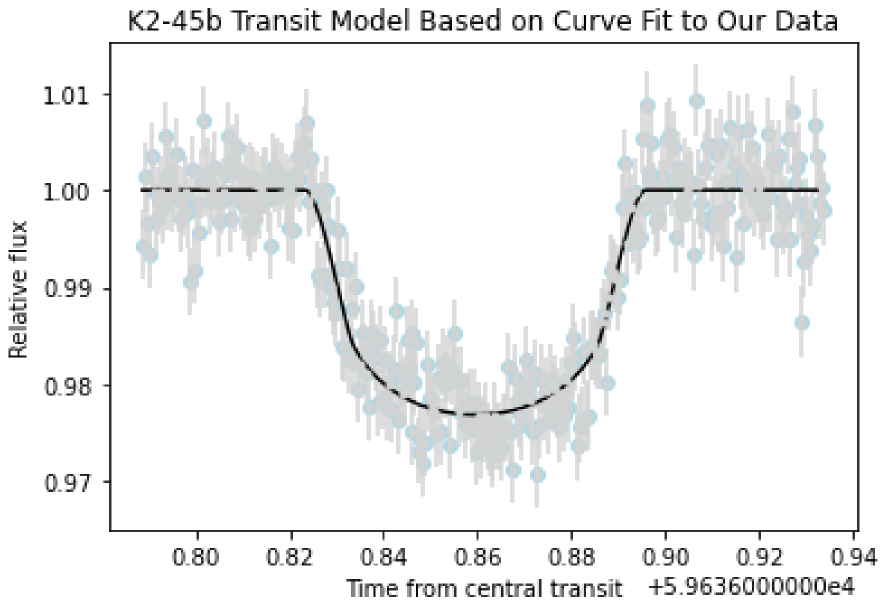

Fig. 1: Scatter Plot of Relative Flux data from transit containing error bars with an overlay of the curve fit based on parameters calculated using an optimized curve fit of the scatter plot data.

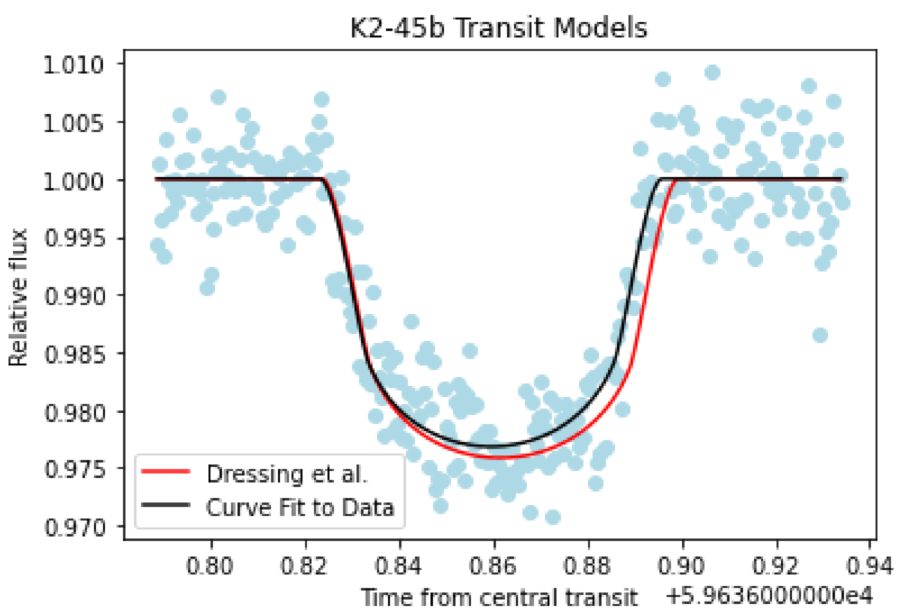

Fig. 2: Scatter Plot of Relative Flux data from transit with an overlay of the curve from the Dressing et al. planet parameters and the optimized curve fit.

Fig. 3: Dressing et al. versus Curve Fit Parameters

	Time of Inferior Conjunction (JD – 2400000)	Planet Radius (in units of stellar radii)	Semi-Major Axis (in units of stellar radii)	Orbital Inclination (degrees)
Dressing et al.	59636.861541	0.139589	8.02	87.75
Curve Fit	59636.8596	0.137620201	8.20559426	87.4060374

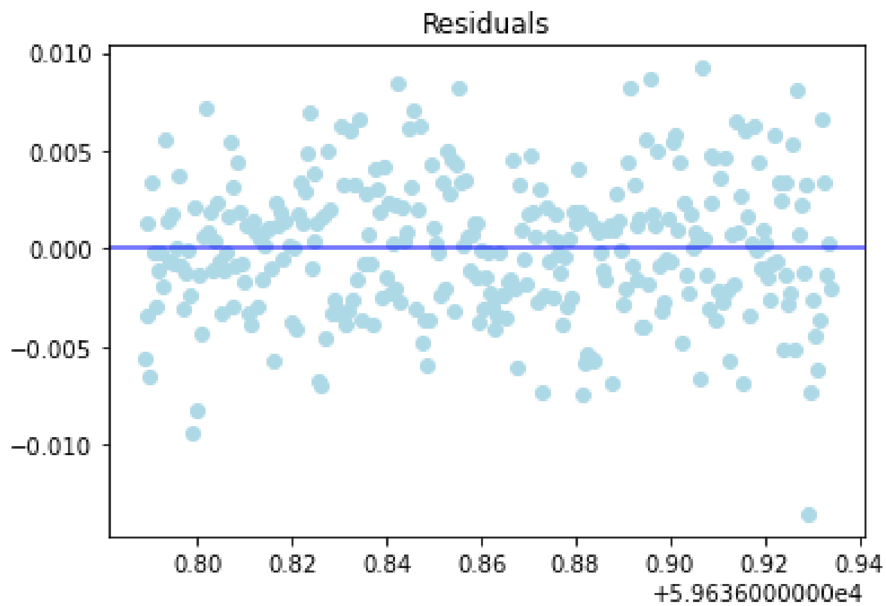

Fig. 4: Scatter Plot of the residuals of the flux data versus time from the central transit. The dark blue line indicates where the residuals are equal to zero. The average of the residuals is approximately 2.7065×10^{-5}. The standard deviation of the residuals is approximately 0.0036.

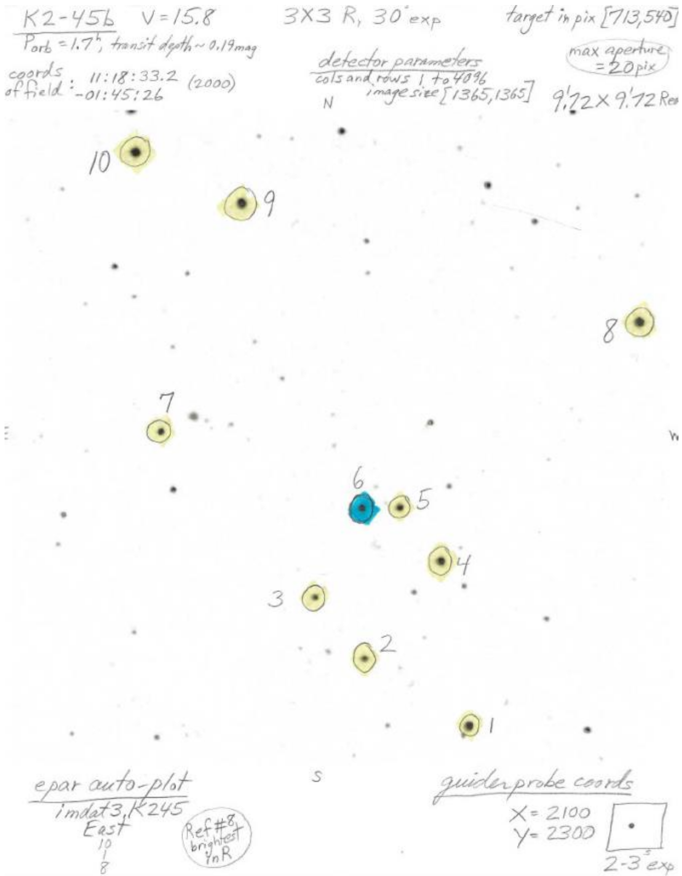

Fig. 5: The finders chart used in the Differential Photometry process to identify the target star and the comparison stars. K2-45, the target star, is highlighted in blue. The comparison stars are highlighted in yellow.

Works Cited

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