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Exoplanet Research: Differential Photometry for Kepler 6b

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Abstract

Since their discovery, exoplanets have become a rich source of potential information on solar system structure and evolution, solar system dynamics, and the prevalence of life in the universe. As part of an exploratory study of exoplanet atmospheres at Humboldt State University, we studied the light curve of the exoplanet Kepler 6b using a student written program to determine the radius and orbital period of this planet. We found the results of our program corroborated the results of previous studies of this same planet. These results allow us to proceed with confidence towards further analysis of this object that we can determine its thermal profile and put constraints on its atmosphere. The end result will be the refinement of a method for analyzing the thermal and atmospheric information of exoplanets in order to better determine the prevalence of Earth-like planets in the universe which are capable of hosting life.

1. Introduction

Extra solar planets, or exoplanets, are planets that lie outside of our solar system. An extrasolar planet can be discovered by the so-called *transit method*, in which the planet passing in front of it's host star will cause the light, we can detect from the star, to dim.[1] With the Kepler telescope or the use of any other CCD camera we can detect a change or decrease in the overall intensity of light from the host star. Measuring this light incident on the CCD is called *photometry*, and measuring the relative amount of light coming from different objects, such as a star and its planets is called *differential photometry*. The Kepler Mission launched in March 2009, spent a little over 4 years monitoring 150,000 stars in the Cygnus-Lyra region with continuous 30 min to 1 min sampling. The primary objective was to detect exoplanet transits with an emphasis for rocky (terrestrial) planets with radius $R < 2.5\ R_{Earth}$ hopefully within the habitable (Goldilocks) zones of Sun-like Stars. The habitable zone is the region around a host star in which a planet can have a temperature and atmosphere that could possess liquid water. This is essential for a planet to support life. As of May 11th, 2016, over 4000 exoplanet candidates have been discovered by the Kepler Spacecraft. We can analyze data from the Kepler Spacecraft to detect and gather information from these exoplanets.

1.1 Primary and Secondary Eclipses

The term light curve describes flux over time, and variations in the light curve signal the presence of a planet.[2] A large periodic dip in the light curve is evidence of a planet transiting in front of its parent star, as the light blocked by the planet will cause a reduction in flux. This is known as the primary eclipse.[3] A much smaller periodic dip is seen when the planet moves behind its star. This, known as the secondary eclipse, is a result of only having the flux of the star where elsewhere in the light curve is the combined light of both star and planet.[4]

1.2 Kepler 6b

Each object discovered by Kepler, referred to as a Kepler Object of Interest (KOI) is given a corresponding ID number so they can be easily accessed through the data archive. After reviewing an article from 2011 that focuses on exoplanets[5], we chose an exoplanet with detailed analysis to use as a template for our research. By selecting a known exoplanet we could also use its KOI ID number to search the Mikulski Archive for Space Telescopes (MAST) database and download the files containing it's light curves. One of the objectives of our research was to create a python program that would help us analyze data and study exoplanets and their characteristics. We can establish a stronger understanding of how to interpret the data by reproducing results of an exoplanet that have been obtained previous to our research. For this study we chose to analyze Kepler 6b, a Jupiter sized planet or- biting a Sun-like star, Kepler 6. Kepler 6 is both more massive, $M_* = 1.21M_s$, and larger than the Sun, $R_* = 1.39R_s$.[6] The orbital period of this planet is 3.2347 Julian Days.[7] Planets such as these are referred to as Hot Jupiters. A "Hot Jupiter" is a planet with a mass of the order, or larger than, the planet Jupiter, but it is closer to its host star than Earth is to our Sun.[8] Due to their short orbital radius, Hot Jupiters are the easiest to detect through the methodology of exoplanet transit.

2. Data Analysis

2.1 Data Pipelines

The data is downloaded from the spacecraft through the Deep Space Network. The Mission Operations Center at the Laboratory for Atmospheric and Space Physics (LASP) receives the data that is organized by type and binned into separate files. This is then sent to the Data Management Center at the Space Telescope Science Institution (STScI), where it is archived for further use. The data is then decompressed and sorted by cadence (long or short) and is converted to the FITS (Flexible Image Transport System) format. This is the form that we can then retrieve online through the Mikulski Archive for Space Telescopes (MAST).[9] Cadence refers to the sampling of the light from the object under investigation. The time between each sample is irregular either by design or circumstance.

From Kepler 6b's fits files we can plot 2 very similar curves as seen in Figure 1. One of the curves represents the Simple Aperture Photometry (SAP) flux, which is the flux or light incident on the aperture of the spacecraft's photometer. The other representing the Pre-Data Conditioned (PDCSAP) flux. PDCSAP accounts for possible systematic errors from the spacecraft, and corrects them providing us with a light curve that corresponds to just features of the host star and exoplanet under investigation.

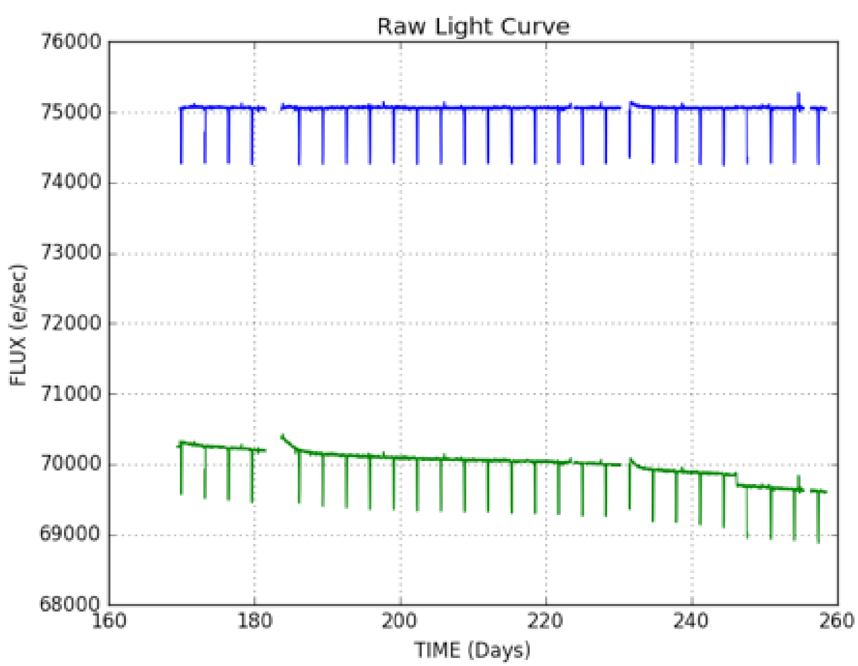

Figure 1: This plot contains two lightcurves. The bottom lightcurve in green represents the SAP flux from the Kepler Spacecraft, whereas the blue curve represents the PDCSAP flux.

2.2 Orbital Period

Focusing on the PDCSAP flux from Figure 1, we can see a period of dramatic change in flux throughout curve. This change in flux is the exoplanet transiting in front of the star. This is referred to as the primary eclipse. To get the orbital period we can take a fourier transform of the data to find the frequency of the primary eclipse. We can see this in Figure 2.

Figure 2 shows two sets of peaks. The first one (which peaks at 80,000 originally) is the correct frequency that leads to the known orbital period for Kepler-6b. We were not able to identify the source of the second set (which peaks at 125,000 originally). More analysis needs to be performed to determine why our data output it. From our data we were able to get an orbital period of 3.234 days.

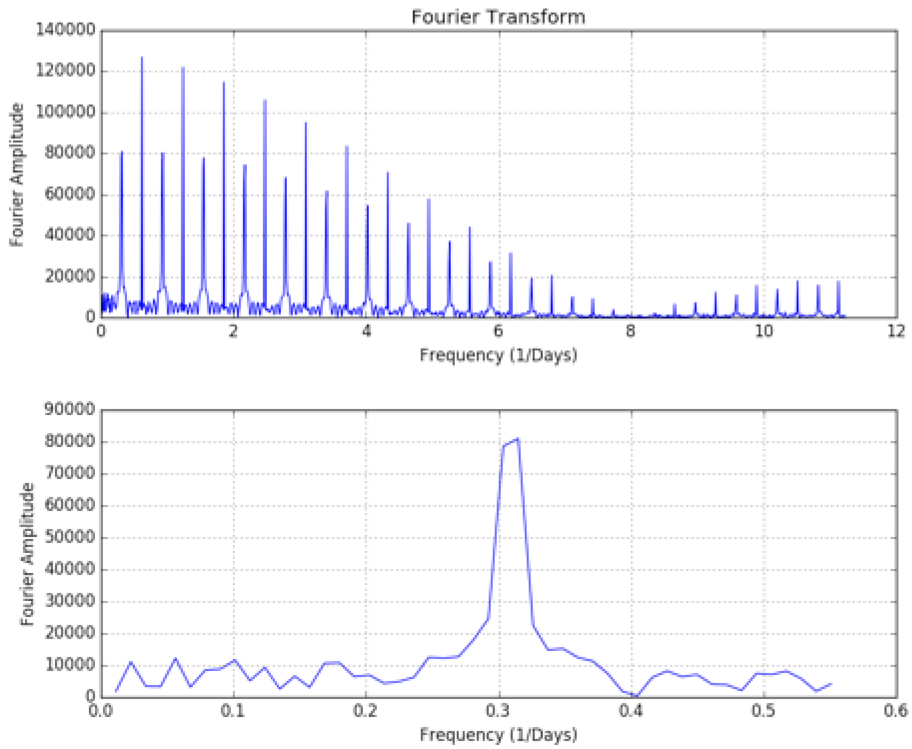

Figure 2: The top plot shows the fourier transform of the PDCSAP flux from the fits file. Our program shows additional peaks which are incorrect and due to unknown factors. The plot below is focused on the fundamental frequency of the primary eclipse.

2.3 Phase-Fold

To improve our data, it is important to phase fold the the entire lightcurve to fit one cycle. For each light curve file the time between samples is not the same (irregular) but we can fill in the gaps of data by folding the cycles of the planet orbiting the star over one another. This will overall improve the Signal to Noise ratio of our observation and define the peak of our primary transit more clearly.

$$\phi = \frac{t - t_0}{P} \tag{1}$$

t is the time of each data point. t_0 is the first data point in each cycle. *P* is the period of the exoplanet. Ø is the new coordinate that would be assigned to each data point. This way we can fit each data point in one period or one phase. With each cycle fit to the same phase our long light curve will turn into a phase-folded light curve as seen in Figure 3.

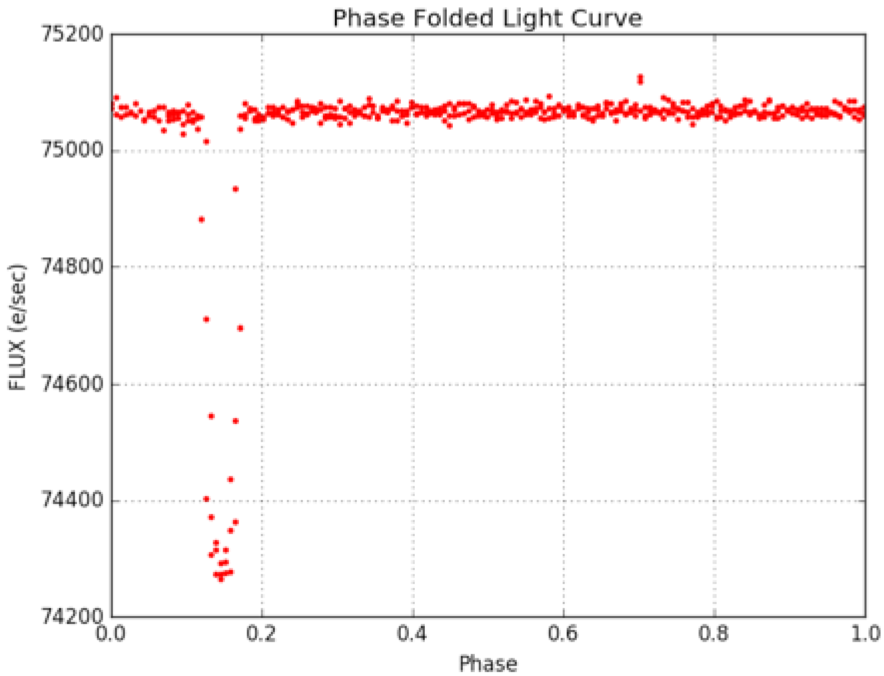

Figure 3: This graph shows the phase-folded light curve. Every data point is fit to the ephemeris, also known as the orbital period of the exoplanet.

2.4 Planet Radius

We are able to relate the radius of the planet from the radius of its host star and their respective flux. The ratio of the planet's flux vs. the star's flux is equivalent to the ratio of the cross-sectional area of the two bodies. We can do this only if we assume that the disk of the star is uniform. The following equation represents this relationship.[10]

$$\frac{F_p}{F_*} = \frac{4\pi R_p^2}{4\pi R_*^2} \qquad (2)$$

F_p is the flux of the planet. F_* is the flux of the host star. R_p is the planet's radius and star's radius $R_* = 1.39 R_s$.[11] We can see in Figure 3, that the steady or "flat" flux is the combination of host star and planet flux not impeding the other. The large drop in flux, ΔF, is the primary transit (planet passing in front of the star). This translates to:

$$\frac{\Delta F}{F_*} = \frac{F_* - (F_* - F_p)}{F_*} = \frac{F_p}{F_*} \qquad (3)$$

To ensure the accuracy of our results, we fit a line to both the average flux and the curve representing the change in flux. The average flux was determined by taking the mean of all data points after the primary eclipse. The curve representing the change in flux was fit to the data points with a second order polynomial function. This is shown in Figure 4. These calculations resulted in F_1 = 75068.799 (e-/s) and F_2 = 74277.855 (e-/s). Utilizing the relationship from earlier results in a planet Radius of 1.44546 R_J, roughly 1.5 times the size of Jupiter.

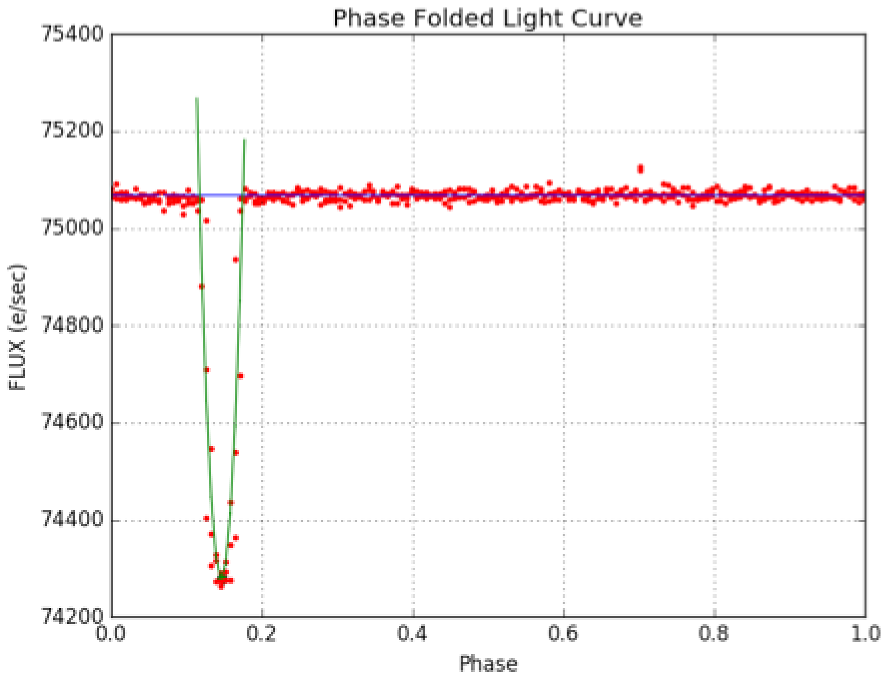

Figure 4: The blue line represents the average of the flux and the green line is fit to the curve. Utilizing this method, we find the minimum value for this curve to better calculate the change in flux.

3. Discussion

We successfully created a python code that plots light curves of exoplanet candidates. For our KOI we successfully calculated the orbital period, and radius. With our program we obtained results which match previous studies.[12] We found our analysis the radius of Kepler 6b to be 1.445 R_J and the ephemeris to be 3.234 days. Prior calculations of the radius and ephemeris using our same methods give values of 1.32 R_J and 3.235 days[13], showing that we are within 0.125 and 0.001 of our expected values. These findings give us confidence in the veracity of our results, prior to error analysis calculations. Error analysis on our program allows us to proceed with the study of the secondary eclipse, which is much fainter than the primary eclipse and will require a high level of ac- curacy. Our ultimate goal is to be able to find the secondary eclipse of the exoplanet to find its effective temperature. When the planet goes behind the star from our view here on Earth there will be a smaller drop in the flux which would give us just the flux of the host star. We would then be able to subtract that from our data and be able to plot the surface flux of the exoplanet under investigation. And after careful study of the units of flux that are provided by MAST we can calculate the effective temperature of the planet.

$$F_S = \sigma_R (T_{eff})^4 \qquad (4)$$

The equation above, The Stefan-Boltzmann Law, relates the effective temperature to the surface flux. σ_R is the Stefan-Boltzmann constant. F_S is the flux from the surface of the planet and T_{eff} is the effective temperature.[14]

4. Future Research

After establishing the basics of interpreting raw Kepler Data into planetary characteristics, we will perform the same calculations but include error analysis. Additionally, we must identify the error in the fourier transform of the original light curve, that caused the peaks in frequency that we observed. Finally, since we are tailoring the code to fit any light curve file that we input into it, we have to input a range of data points that pertain to each individual file. Due to phases of the planet itself (portion of the planet that reflects light from its host star) the flux of the planet will increase gradually during a single period. If we fit a line to the data points directly before and after the primary eclipse, we can get a better average.

Our long term goal is to have a working program from which we can accurately extract the secondary eclipse data from any Kepler KOI file. Once we have demonstrated that we can do this successfully, we will want to select a number of candidates to subject to this analysis. Using the 76 Kepler Objects of Interest identified in Coughlin's 2011 paper, we will select a sample of suitable objects for secondary eclipse analysis. We can then take steps towards using our program to extract the same data from different planetary types.

About the Authors

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3. Ibid.

4. Ibid.

5. J. L., Coughlin, and M. Lopez-Morales. "A Uniform Search for Secondary Eclipses of Hot Jupiters in Kepler Q2 Light Curves," The Astronomical Journal, 143 no. 2. (2012).

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