Calculating Properties of Exoplanets Observed by the Kepler and K2 Missions with Python's Lightkurve

P. M. Jackson*

Department of Physics, Auburn University, Auburn, AL, USA

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Abstract

Using light curves produced by the transit method allows for the partial characterization of exoplanets. For this project, I created a python script that downloads data from missions, manipulates and analyzes the light curve, and produces values for the exoplanet's orbital period, orbital distance, radius, and effective temperature. I picked 5 confirmed exoplanets that met the following criteria to test my script's accuracy: (i) observation made by Kepler or K2 mission, (ii) exists as the only planet in its stellar system, (iii) exists in a single-stellar system, and (iv) has the previously mentioned variables available (to check my values against). These exoplanets were K2-260b, Kepler-12b, Kepler-15b, Kepler-4b, and K2-143b. The values produced for the all targets were accurate with an average percent error of less than 3%. Thus, the code is able to very accurately determine certain properties of exoplanets from transit light curves.

I. INTRODUCTION

Exoplanet hunting is one of the newest additions to the scene of astrophysical research. the first confirmed exoplanet wasn't until 1995 and, more recently, in 2009, NASA launched the Kepler Space Telescope which would quickly open the flood gates to discovering planets beyond our solar system. Due to some complications with the craft's reaction wheels, the primary mission was ended, though Kepler was eventually reinstated to planet hunting in the "K2" mission [1]. Kepler's main method of planet detection was the transit method, where a planet passing in front of its host star causes a decrease in total flux observed by the telescope.This decrease in flux produces a light curve and can provide information about the planet's radius and orbital period. With that information and some simple math, we can then calculate the planet's distance from its star and the planet's temperature. The importance of being able to determine these properties is that it allows us to paint a better picture of what solar systems beyond our own are like and how ours compares to them. It enables us to understand how common exoplanets are and better determine the likelihood that life exists beyond earth. This data is a step forward among many that leads humanity towards more fully understanding our place in the universe.

* pmj0008@auburn.edu

II. METHODS

I used the programming language Python with the Lightkurve module [2] to create a script that automates the process of obtaining and analyzing SAP and PDCSAP fluxes from the Kepler and K2 missions. SAP flux stands for Simple Aperture Photometry (SAP) flux. This type of data has not been processed, so it may still contain errors (such as "thermal gradients across the spacecraft" or "pointing variation") [3]. PDCSAP flux is Pre-search Data Conditioning SAP flux. This data is SAP flux that has been processed and refined by NASA's Kepler Data Processing Pipeline. These fluxes were used to obtain the exoplanet's orbital period which then allows for the calculation of orbital distance, planet radius, and temperature of the orbiting exoplanet.

A. The Input File

After importing the appropriate modules (Numpy, Lightkurve, Matplotlib, XLRD), the code reads an input (excel) file with data necessary for the script to run. This data is input by the user and contains the information: (a) the stellar system's Kepler or K2 number ID, (b) the quarter of observation (when the observation took place), (c) the stellar host's mass in solar masses, (d) the stellar host's radius in solar radii, and (e) the stellar host's equilibrium temperature in kelvin. This information was gathered from NASA's Exoplanet Archive corresponding to the stellar system being observed [4]. The code then prints these values for the user to see.

B. Importing Target Pixel File and Extracting Light Curve

Next, the code will access the Mikulski Archive for Space Telescopes (MAST) [5] and downloads the target's (specified in the input file) "Target Pixel File" (TPF). An aperture mask is applied to the TPF to highlight the pixels that contain the most information from the observation (Fig. 1). From this TPF, a light curve can then be extracted (Fig. 2). This light curve is composed of the SAP flux I mentioned earlier. Using this data, if we know the orbital period of the exoplanet, we can then manually fold the lightcurve on itself at intervals of that value (Fig. 3). The folding allows for the superposition of multiple dips in

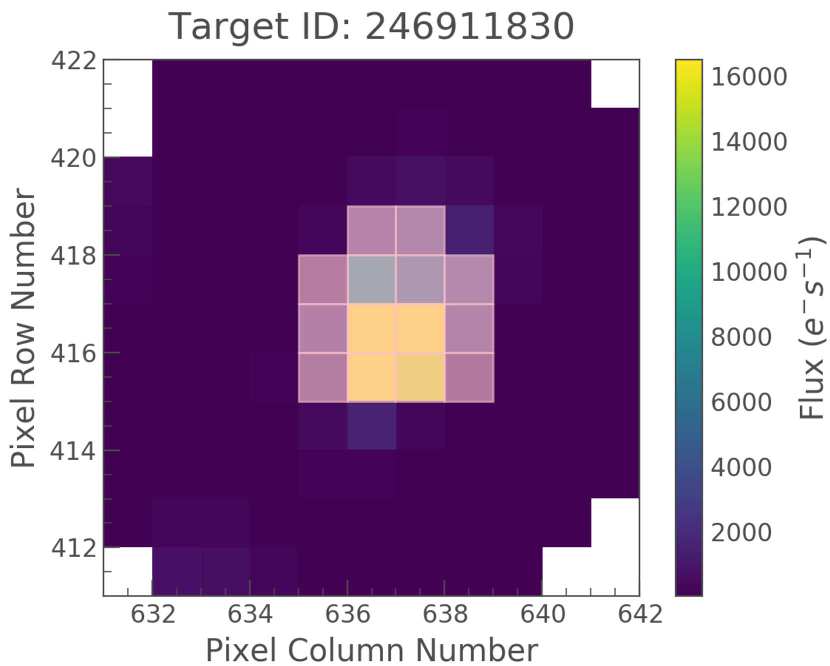


FIG. 1: Target Pixel File of EPIC 246911830 (K2-260) as observed by K2, quarter 13. The highlighted pixels represent where the best data for light curve extraction exists

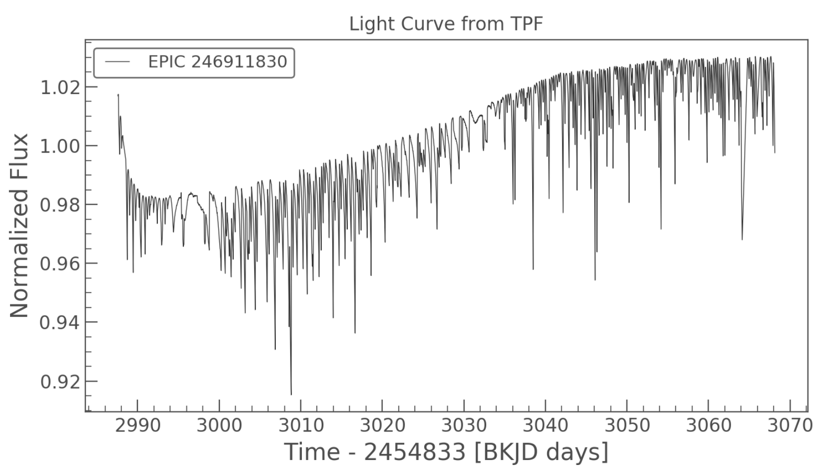


FIG. 2: SAP flux extracted from TPF

the light curve so that the dip becomes more well defined.

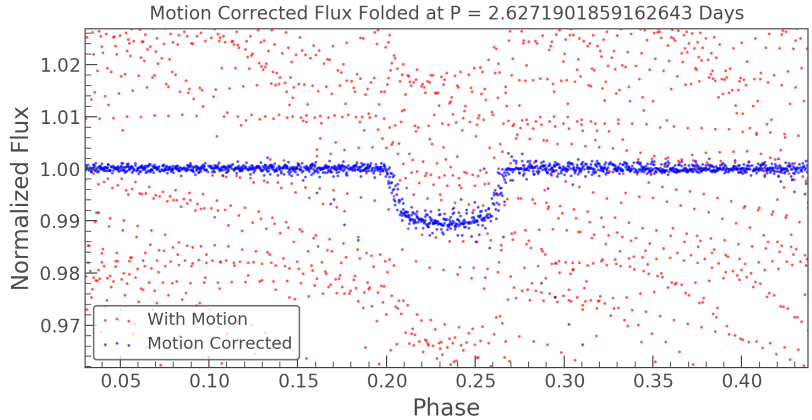


FIG. 3: Raw and motion corrected light curves of K2-260 folded at a period of 2.6271 days

C. Using Light Curves from NASA's Kepler Data Processing Pipeline

Because SAP flux may contain a variety or errors, Lightkurve's processing may not be able to totally strip the data of flaws. Thus, it is often preferred to use PDCSAP flux light curves instead. These can be obtained, like the TPFs, through MAST.

In the same manner we obtained the TPF, the code accesses MAST and imports the target's PDCSAP flux (Fig. 4). From here, this new light curve is initially converted to a periodogram in the frequency domain and then converted to the period domain. The period that exhibits maximal power is taken to be the orbital period of the exoplanet. In the same way we folded the refined SAP flux, we can also fold the PDCSAP flux – except now the code has automatically calculated and used the value of the orbital period instead of through manual input (Fig. 5).

Thus, the code generates two nearly identical light curves via different methods and data.

D. Calculating Orbital Distance, Planet Radius, and Temperature

Once the orbital period is known, it is a simple task to calculate these other parameters. Orbital distance can be calculated by rearranging Newton's version of Kepler's Third Law to read:

$$a = \sqrt[3]{G\frac{MP^2}{4\pi^2}} \tag{1}$$

where a is the orbital distance, G is the gravitational constant, M is the mass of the host

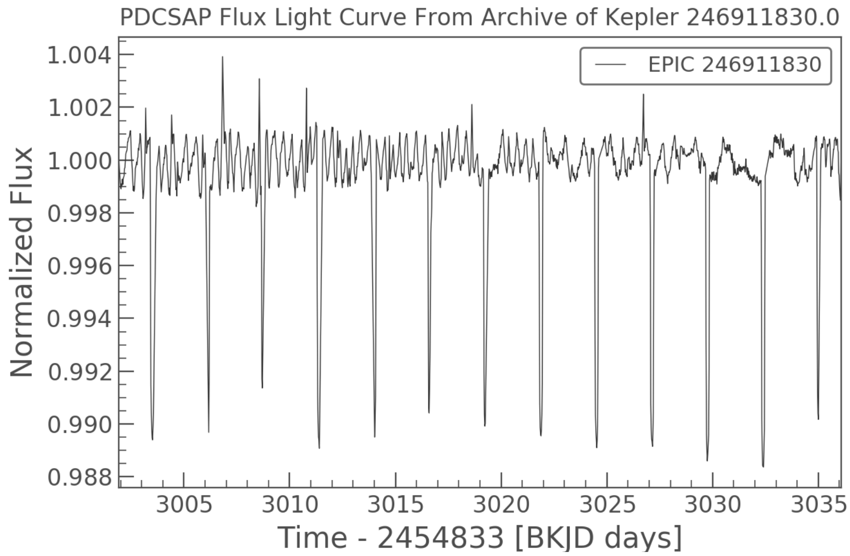


FIG. 4: PDCSAP Flux obtained from MAST

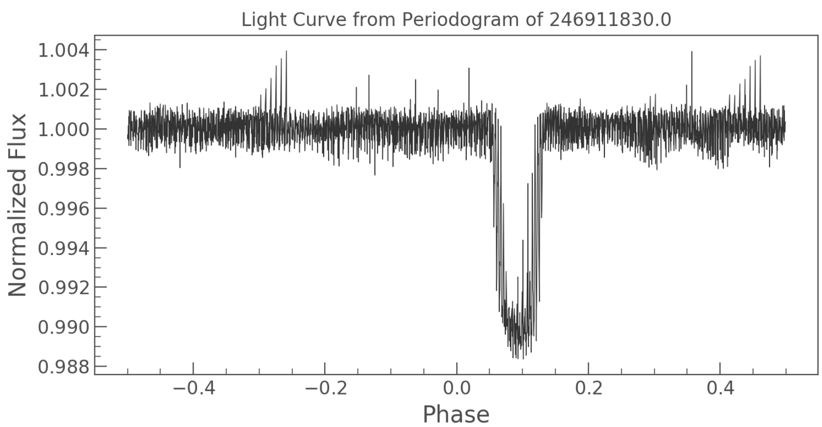


FIG. 5: Light Curve from PDCSAP flux periodogram folded at 1 phase = 2.6271 days

star, and P is the orbital period.

Calculating the radius of the planet needs one more piece of information: the depth of the transit which is defined as

$$Depth = 1 - minimum \tag{2}$$

where the *minimum* value must be manually put into the code by the user. It can be obtained from either of the final light curves generated (Fig. 3 or Fig. 4) by taking the minimum flux value of the dip [6] - this value is typically very small, between a hundredth to the whole of a percent. Once this value is obtained and placed into the code, the exoplanet's radius can be calculated using

$$R_p = R_* \sqrt{Depth} \tag{3}$$

where R_p is the radius of the planet and R_* is the radius of the host star.

Finally, the equilibrium temperature of the planet can be estimated from

$$T_p = T_* (1 - A)^{1/4} \sqrt{\frac{R_*}{2a}} \tag{4}$$

where T_p is the equilibrium temperature of the planet, T_* is the average temperature of the host star and A is albedo[7].

E. Stellar Systems / Exoplanets Tested

Stellar systems with an exoplanet that met the following criteria were chosen as test candidates: (i) observation made by Kepler or K2 mission, (ii) exists as the only planet in its stellar system, (iii) exists in a single-star system, and (iv) has the previously mentioned parameters available. This allows for the comparison of the code's calculated values to the actual confirmed values such that the code's accuracy can be determined. The light curves of the following systems were analyzed:

Alias	Kepler ID	Mission	Quarter
K2-260	246911830	K2	13
Kepler-12	11804465	Kepler	11
Kepler-15	11359879	Kepler	4
Kepler-4	11853905	Kepler	4
K2-143	216414930	K2	7

TABLE I: Stellar Systems Tested

III. RESULTS

For sake of organization, I will dedicate a page per system analyzed with all relevant graphs and data at the end of the paper. Figures from the system K2-260 have already been shown, but will still be included at the end.

All of the systems analyzed by the code show decent precision in calculating parameters with an average percent error of less than 3%. In fact, the most significant contributor to this error comes from the estimation of the planet's radius, which requires the user to manually input the "minimum" flux value. So, resolving human error, the code can calculate values to an accuracy of less than 1% error. The code clearly relies on observed data from spacecraft, so accurate observational data is vital.

IV. CONCLUSIONS

In this project, I used python and the Lightkurve module to analyze light curves from the Kepler and K2 missions. Five different stellar systems were analyzed and the values of orbital period, distance, planet radius, and temperature, generated by the code were compared with confirmed values from NASA's Exoplanet Archive. The first four systems displayed in this paper support the code's accuracy with an average percent error of less than 3%. The code is mostly automated, but some manual input is needed to ensure accurate results. With some more work, this could likely be automated so that one would simply specify the system they wish to analyze and the code would provide the most accurate results it can produce with the data provided. Though it does already provide accurate results, there is always room for improvement.

[1] NASA, About exoplanets, website (), `https://exoplanets.nasa.gov/what-is-an-exoplanet/about-exoplanets/`.

[2] Lightkurve Collaboration, J. V. d. M. Cardoso, C. Hedges, M. Gully-Santiago, N. Saunders, A. M. Cody, T. Barclay, O. Hall, S. Sagear, E. Turtelboom, J. Zhang, A. Tzanidakis, K. Mighell, J. Coughlin, K. Bell, Z. Berta-Thompson, P. Williams, J. Dotson, and G. Barentsen, Lightkurve:

Kepler and TESS time series analysis in Python, Astrophysics Source Code Library (2018), ascl:1812.013.

[3] K. Kinemuchi, M. Fanelli, J. Pepper, M. Still, and S. B. Howell, Demystifying kepler data: A primer for systematic artifact mitigation, Publications of the Astronomical Society of the Pacific **124**, 963–984 (2012).

[4] NASA, Nasa exoplanet archive, website (), `https://exoplanetarchive.ipac.caltech.edu/index.html`.

[5] S. T. S. Institute, The mikulski archive for space telescopes, website, `https://archive.stsci.edu/`.

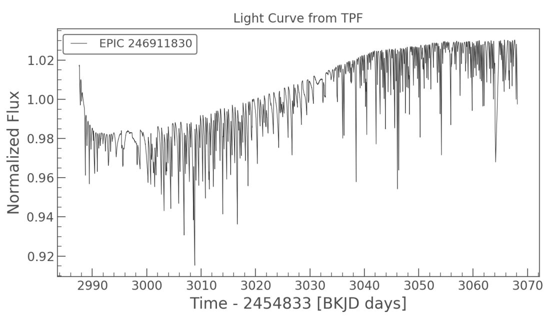
[6] "Minimum" here is not the absolute minimum value of the dip. There is a spread of values that are the "minimum", so one should really take the average of all these values. This can be quickly estimated by viewing the floor of the dip as a rectangle and using the value at the center of that rectangle as the minimum value.

[7] Assumed to be 0.

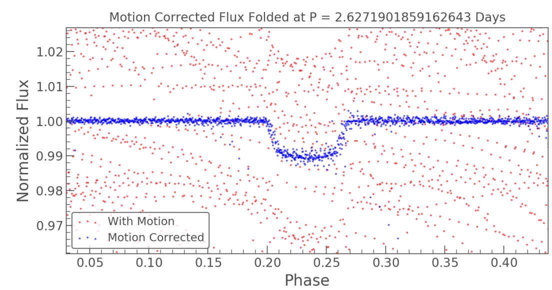
1. K2–260 [EPIC 246911830]

	Orbital Period (Days)	Orbital Distance (AU)	Planet Radius (Rjupiter)	Planet Temperature (K)
Calculated	2.6263	0.0415	1.723	1957.3
Actual	2.6266	0.0404	1.552	1957
% Difference	0.0108	2.918	11.069	0.018

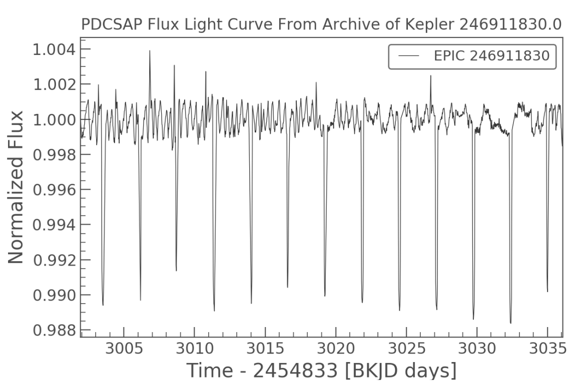
TABLE II: Calculated parameters vs. actual parameters of K2-260 b



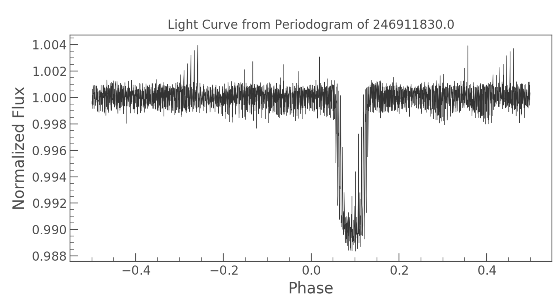
(a) (Fig. 2 Restated) SAP flux extracted from TPF



(b) (Fig. 3 Restated) Raw and motion corrected light curves of K2-260 folded at a period of 2.6271 days



(c) (Fig. 4 Restated) PDCSAP Flux obtained from MAST

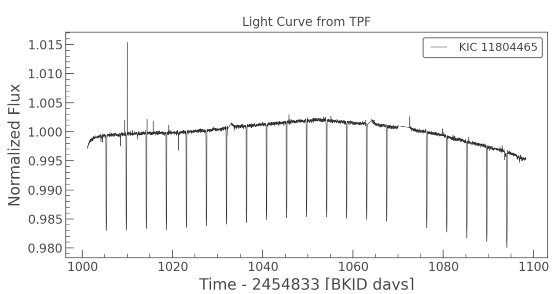


(d) (Fig. 5 Restated) Light Curve from PDCSAP flux periodogram folded at 1 phase = 2.627 days

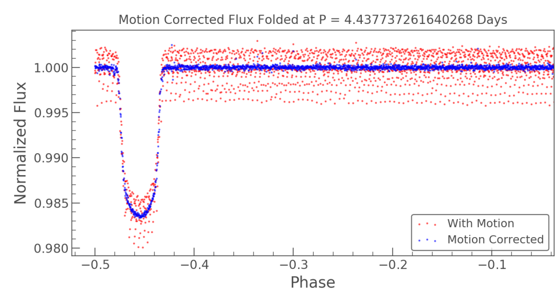
2. Kepler-12 [KIC 11804465]

	Orbital Period (Days)	Orbital Distance (AU)	Planet Radius (Rjupiter)	Planet Temperature (K)
Calculated	4.433	0.0555	1.831	1481
Actual	4.437	0.0553	1.695	1480
% Difference	0.098	0.533	8.06	0.07

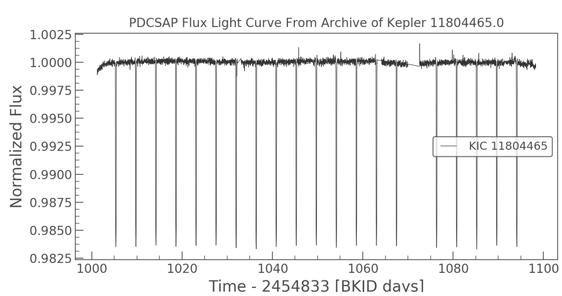
TABLE III: Calculated parameters vs. actual parameters of Kepler-12b



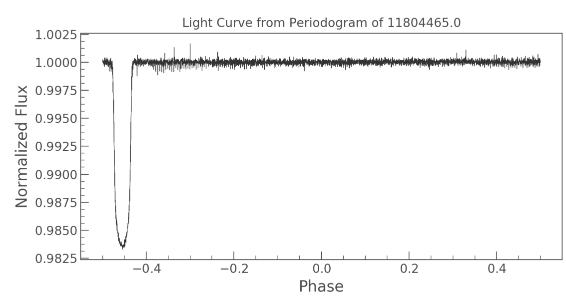
(a) SAP flux extracted from TPF



(b) Raw and motion corrected light curves of K-12 folded at a period of 4.437 days



(c) PDCSAP Flux obtained from MAST

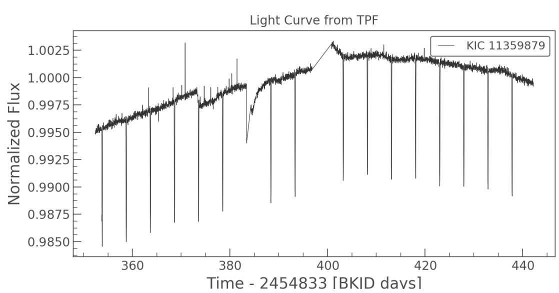


(d) Light Curve from PDCSAP flux periodogram folded at 1 phase = 4.437 days

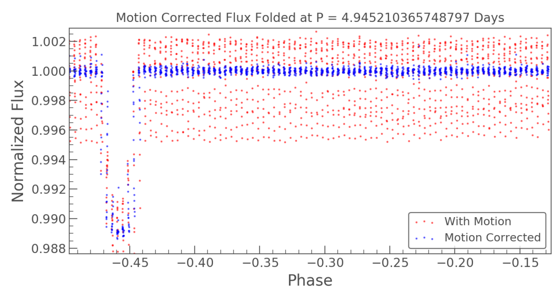
3. Kepler-15 [KIC 11359879]

	Orbital Period (Days)	Orbital Distance (AU)	Planet Radius (Rjupiter)	Planet Temperature (K)
Calculated	4.947	0.05716	1.021	1107.7
Actual	4.942	0.05714	0.96	1251
% Difference	0.105	0.0507	6.375	11.4

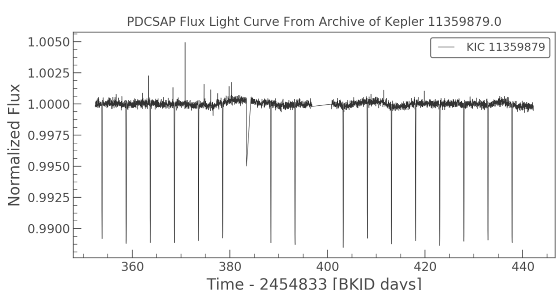
TABLE IV: Calculated parameters vs. actual parameters of Kepler-15b



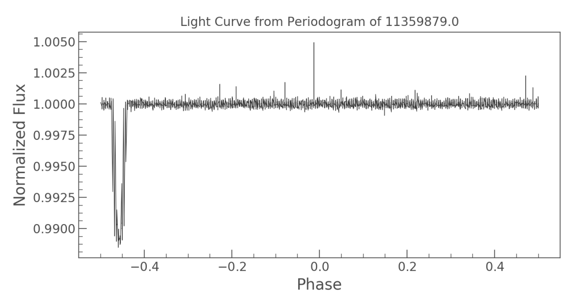
(a) SAP flux extracted from TPF



(b) Raw and motion corrected light curves of K-15 folded at a period of 4.945 days



(c) PDCSAP Flux obtained from MAST

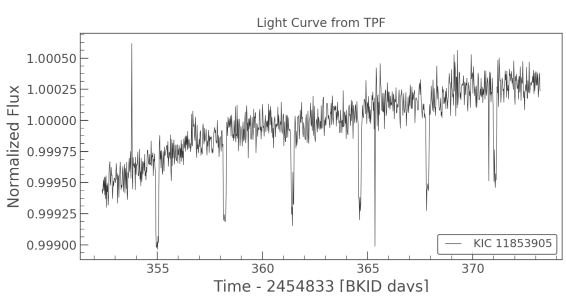


(d) Light Curve from PDCSAP flux periodogram folded at 1 phase = 4.945 days

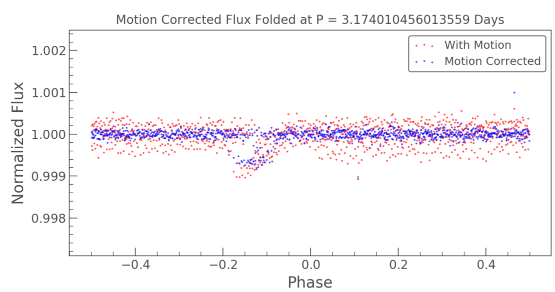
4. Kepler-4 [KIC 11853905]

	Orbital Period (Days)	Orbital Distance (AU)	Planet Radius (Rjupiter)	Planet Temperature (K)
Calculated	3.186	0.0453	0.402	1617.6
Actual	3.213	0.0456	0.357	1650
% Difference	0.824	0.598	12.772	1.9

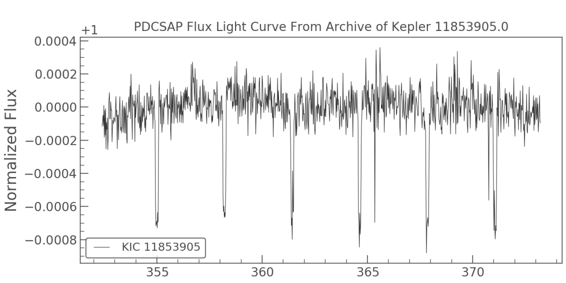
TABLE V: Calculated parameters vs. actual parameters of Kepler-4b



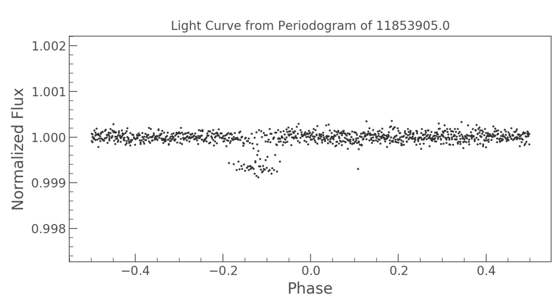
(a) SAP flux extracted from TPF



(b) Raw and motion corrected light curves of K-4 folded at a period of 3.174 days



(c) PDCSAP Flux obtained from MAST

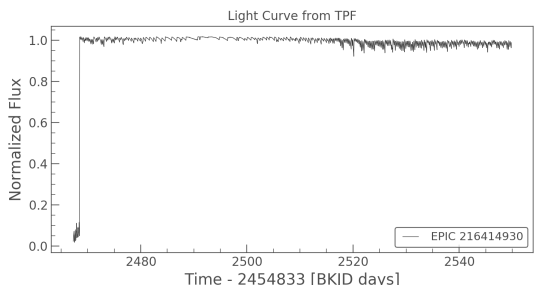


(d) Light Curve from PDCSAP flux periodogram folded at 1 phase = 3.174 days

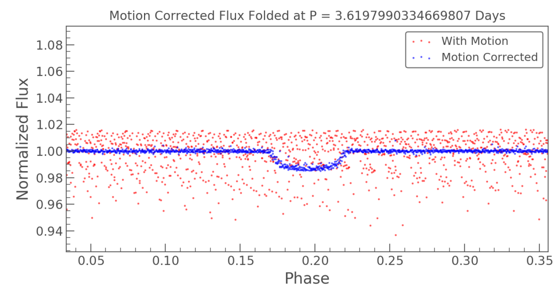
5. K2-143 [EPIC 216414930]

	Orbital Period (Days)	Orbital Distance (AU)	Planet Radius (Rjupiter)	Planet Temperature (K)
Calculated	3.6197	0.05074	1.774	1743.4
Actual	3.6191	0.0507	1.609	1596
% Difference	0.016	0.007	10.27	9.2

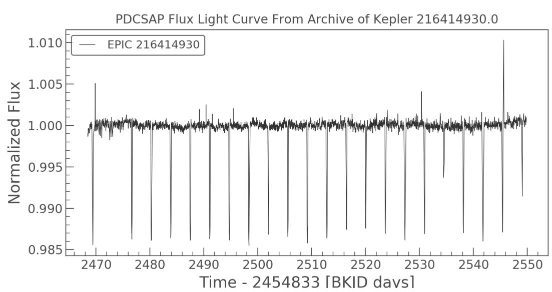
TABLE VI: Calculated parameters vs. actual parameters of K2-143b



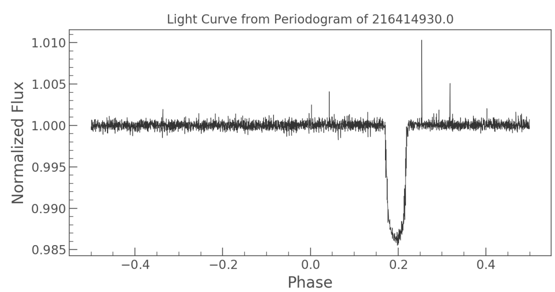
(a) SAP flux extracted from TPF



(b) Raw and motion corrected light curves of K-4 folded at a period of 3.612 days



(c) PDCSAP Flux obtained from MAST



(d) Light Curve from PDCSAP flux periodogram folded at 1 phase = 3.612 days