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Analyzing light curves to highlight phenomena and trends in planetary systems that house terrestrial exoplanets

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Abstract. Light curves describe the luminosity, or flux, emitted by celestial bodies or systems over a period of time. Since light curves are mostly irregular and may contain spikes and dips caused by extraneous factors, they contain valuable information about various phenomena and trends in the observed planetary system. For instance, light curves often help detect exoplanets in a star's planetary system. Furthermore, they also help characterize solar flares, cataclysmic variables (CVs), and various other phenomena. This study collects data in the form of light curves from stars in planetary systems housing terrestrial exoplanets found on the NASA Exoplanet Catalog and explored various causes for variations in the planetary system's light curve. One significant finding from light curve analysis was the possible existence of instrumental noise on the Kepler telescope in quarter 10. However, a larger exoplanet sample size and a real significance test are required for confirmation. This study exemplifies the accessibility and therefore feasibility of gathering data, graphing, and analyzing light curves.

Keywords: Light curves, Terrestrial exoplanets, NASA Exoplanet Catalog, Feasibility.

1. Introduction

1.1. Life & Exoplanets

Life is rare — according to current understandings, Earth is the only planet that harbors life. However, the Drake equation concludes that the existence of extraterrestrial intelligent life is a possibility. The equation evaluates the number of existing advanced civilizations given various factors such as the rate of star formation (denoted R$*$ as shown in Equation (1)) and the number of potentially habitable exoplanets ne. Determining the approximate value of these variables will further existing knowledge of the universe and help gauge the true potential for extraterrestrial life [1].

$$The\ Drake\ Equation: N = R * * fp * ne * fl * fi * fc * L \tag{1}$$

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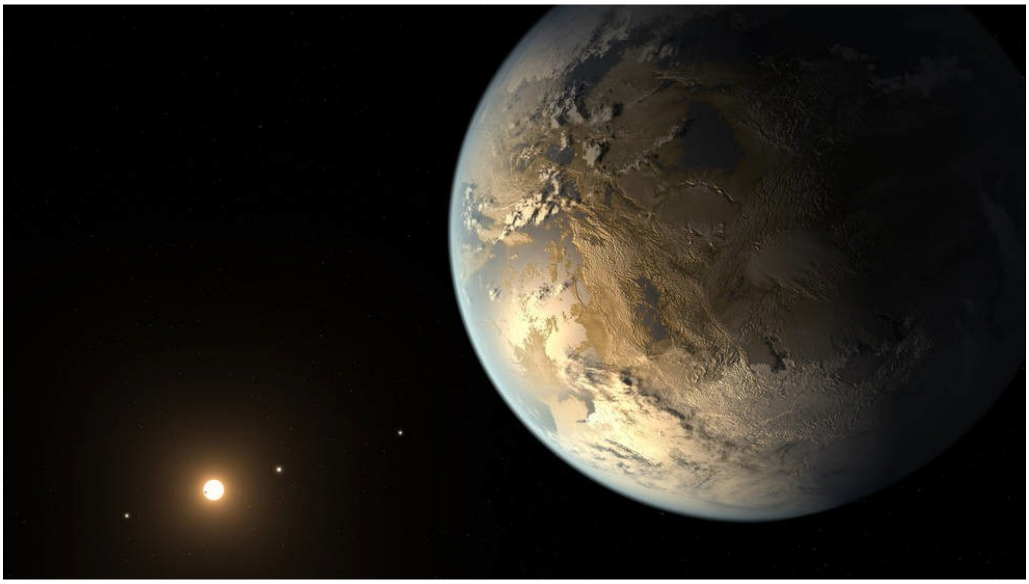

Figure 1. Kepler-186f (artist's concept) is a potentially habitable terrestrial exoplanet discovered by NASA from the Kepler telescope [2].

Although most variables within the Drake Equation will remain unknown for a long time, learning more about exoplanets will heighten the chances of answering the question regarding the existence of extraterrestrial life (see Figure 1. The first exoplanet was discovered in the 1990s, and since then, more than 5000 have been confirmed [3,4]. But what exactly are exoplanets? Exoplanets are any planets outside of the Solar System that revolve around another star. The Milky Way houses billions of stars, each capable of containing several exoplanets. Because every exoplanet's chemical composition is unique, astronomers classify them based on their size and composition. For example, looking at the Solar System, Jupiter is a gas giant (because it is mostly composed of gassy elements), and Earth is a terrestrial planet (because it has a rocky surface, a crust). According to NASA, there are four main categories of exoplanets: Gas giant, super-Earth, Neptune-like, and terrestrial [5]. In this paper, terrestrial exoplanets are explored because they have the highest probability of containing the necessary conditions to support life. A certain subset of terrestrial exoplanets is potentially habitable. To achieve that title, exoplanets must meet several constraints – for instance, they must be at the right temperature (Goldilocks Zone — the planet must be at the right distance from its host star), and its atmosphere must be sufficiently large to protect the planet from harmful solar radiation. One way to determine exoplanet habitability and address these lingering questions is to study the light curves of terrestrial exoplanets, which will be discussed in more detail in the next section.

1.2. Light Curves

In every planetary system, celestial bodies emit light, even smaller trans-Neptunian-like objects (TNOs, albeit with different intensities [6]. To observe and study the properties of exoplanets, astronomers analyze light curves from their host star. Whenever a planet passes between the observer and the host star, the total light (quantified by flux) received temporarily decreases. Hence, by meticulously examining a star's light curve, astronomers can pinpoint specific areas of decreased luminosity (flux) and confirm the existence of an exoplanet. This way of discovering exoplanets is known as the transit method (direct imaging; refer to Figure 2a), although there are several other mechanisms such as gravitational microlensing and Doppler spectroscopy [7]. Unfortunately, variability in an exoplanet's light curve is often not caused by exoplanets, so it is especially important to understand what those factors may be to avoid false exoplanet confirmations. Generally, variability is distinguished by whether it is extrinsic or intrinsic. Extrinsic variables are caused by external factors unrelated to changes with the actual star. Some extrinsic variables include eclipsing variables (exoplanets), rotating variables (starspots), and microlensing variables (gravity bending light). Intrinsic variables are caused by changes in the physical properties of the actual star, which include pulsating variables (changes with stellar radii), eruptive

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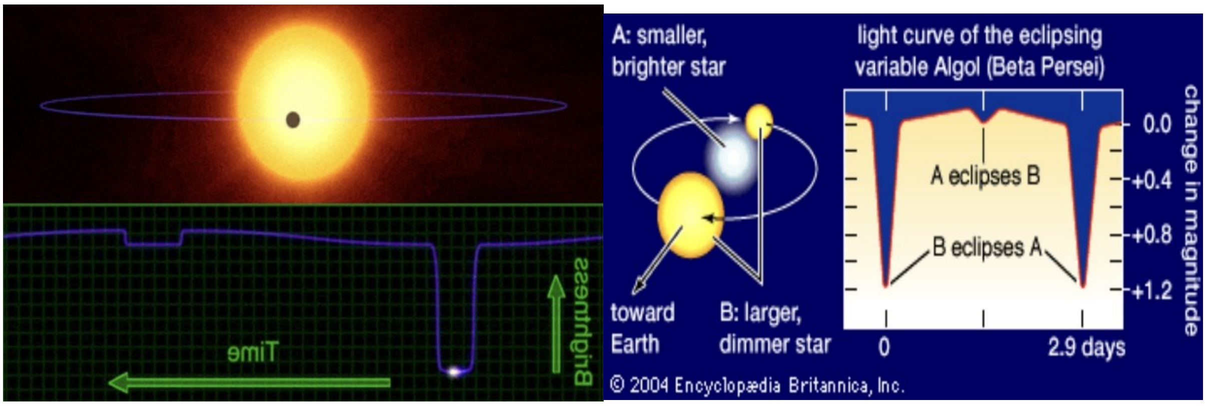
variables (mass ejections), cataclysmic variables (binary systems emitting large amplitudes), and x-ray variables (binary systems that contain either black holes or neutron stars) [7, 8]. Therefore, in addition to the existence of exoplanets, light curves inform astronomers about the existence of a binary star system (see Figure 2b), solar flares, star spots, supernovae, or potential instrumental noise. Astronomers also classify variability.



(a) Transit Method, Astronomy Stack Exchange (b) Binary Star System, Britannica

Figure 2. Applications of light curves in planetary systems [9,10].

As cepheid (meaning periodic), or aperiodic. For example, in planetary systems, eclipsing variables are mostly cepheid, while cataclysmic variables (CVs) are aperiodic [11]. To analyze phenomena in a planetary system, astronomers analyze the host star's light curve. Every light curve plots the flux emitted by a star within a specified period, however, astronomers often use different types of light curves to better understand data. For example, one particularly useful variation of a standard light curve is a periodogram, which folds each time period (quarter) onto itself and graphs the fluxes stacked on each other [12]. A periodogram allows astronomers to determine whether certain variables are periodic or cepheid. Additionally, light curves may be stitched, which stretches the time period for the plot across all quarters when the telescope was active. Ultimately, each type of graphical representation provides different information about the chosen planetary system. It can even convey information about an exoplanet's atmospheric composition [13]. Fundamentally, light curves are graphed based on pixel plots, which show the relationship between pixelated estimations of the observed object and its respective flux. This paper focuses on the light curves of host stars of terrestrial exoplanets and gives a rudimentary example of the process by which astronomers discover various phenomena and trends in the star's planetary system. Information gathered from light curves may also provide hints about the conditions on exoplanets, which may assist in confirming potentially habitable exoplanets and, in the long run, help quantify the probability of the presence of extraterrestrial life. The overarching goal of this paper is to demonstrate the feasibility of analyzing light curves of exoplanets as every tool used in this paper can be found on the internet free of charge.

2. Methodology & Results

2.1. NASA Exoplanet Catalog

The NASA Exoplanet Catalog is a quick and effective method to search for exoplanets. Before searching, filter the results to terrestrial exoplanets discovered by Kepler, which implies that all exoplanets analyzed in this paper were discovered by the Kepler telescope. The website: https://exoplanets.nasa.gov/discovery/exoplanet-catalog/

2.2. Lightkurve Package

After choosing which exoplanets to analyze, download and use the Lightkurve package on Python to help graph different plots.

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2.3. Code

Below is the code that applies both the Lightkurve package and Matplotlib to plot the following:

- Stitched (all quarters) standard light curves.
- Pixel plots (quarter = 4)
- Periodograms (stitched)

Simply call these functions and input the official planet name (ID) as the argument to produce the light curve for that planet's system.

2.3.1. Lightkurve Code

Algorithm 1. Plotting Stitched Light Curves

Input:
Formal name (ID) of exoplanet as stated on the official NASA Catalog
Output:
Stitched (all past quarters) light curve for the exoplanet passed through as the parameter.
Begin

```
def lightcurve(planetid):
        lc = search_lightcurve(planetid, author="Kepler", cadence="long")
        lc_collection = lc.download_all()
        lc_stitched = lc_collection.stitch()
        lc_stitched.scatter()
        flat_lc = lc_stitched.flatten(window_length=401)
        flat_lc.scatter();
        plt.show();
```

End

Algorithm 2. Plotting Target Pixel Files

Input: Formal name (ID) of exoplanet as stated on the official NASA Catalog
Output: Pixel plot for the exoplanet passed through as the parameter
Begin

```
def pixelplot(planetid):
        tpf = search_targetpixelfile(planetid, quarter=4).download(quality_bitmask='hardest')
        tpf.plot(frame=0)
        plt.show();
```

End

Algorithm 3. Plotting Stitched Periodogram

Input: Formal name (ID) of exoplanet as stated on the official NASA Catalog
Output: Periodogram for the exoplanet passed through as the parameter
Begin

```
def periodogram(planetid):
        lc = search_lightcurve(planetid, author="Kepler", cadence="long")
        lc_collection = lc.download_all()
        lc_stitched = lc_collection.stitch()
        pg = lc_stitched.to_periodogram(oversample_factor=1)
        lc_stitched.fold(period=pg.period_at_max_power).scatter();
    plt.show();
```

End

Slight variations of the functions can be used to plot the graphs shown in section 2.4 and 2.5.

2.4. Light Curve Plots

Using the code, Figure 3 shows a sample of different flux graphs for the planetary system that houses Kepler-186f, a potentially habitable terrestrial exoplanet.

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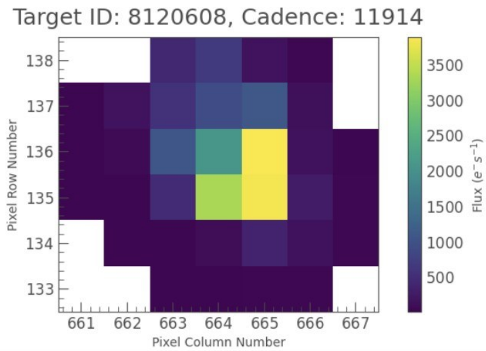
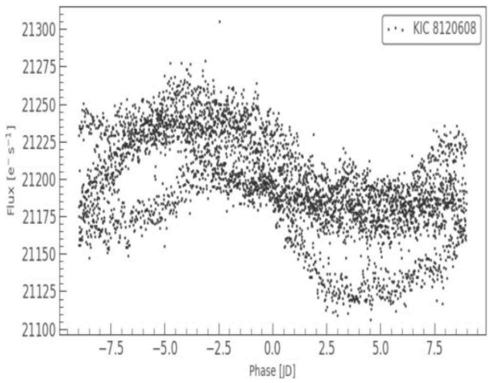
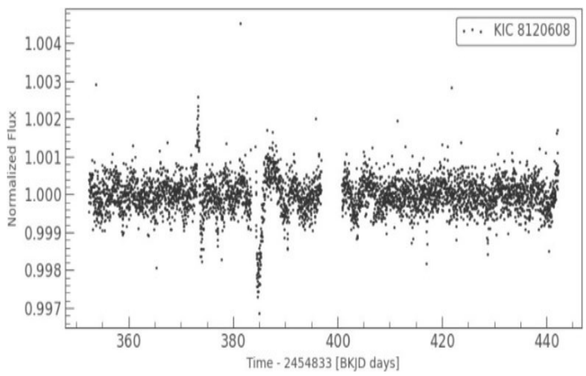


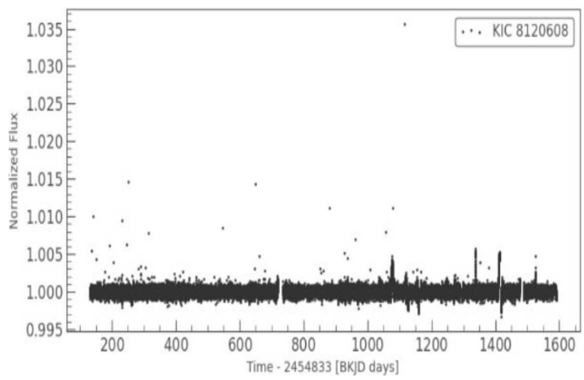
(a) Pixel Plot



(b) Periodogram



(c) Quarter 4 Curve



(d) Stitched (All Quarters)

Figure 3. Flux diagrams for the planetary system housing Kepler-186f [Owner-draw].

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2.5. Light Curves & Analysis

Table 1. Terrestrial Exoplanets - Light Curves & Analysis [14-23].

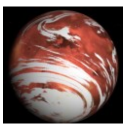
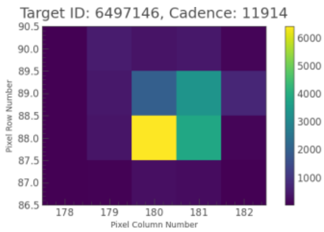
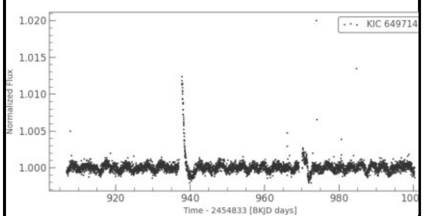
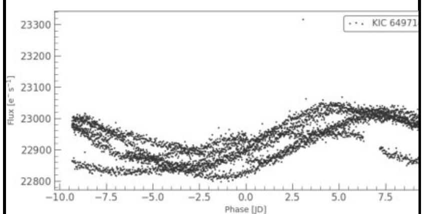
Exoplanet Name [14-18]	Exoplanet Image [19-23]	Plots in the order of 1: Pixel plot for the specified quarter 2: Light curve for the specified quarter 3: Periodogram for the specified quarter [Owner-draw]	Light Curve Analysis
Kepler-438b KIC 6497146		  	Period: ~ 18.680226139602016 d <u>Quarter: 10</u> Peak Analysis: Peaks have similar fluxes but vastly different phases Gaps: ~938 BKJD, ~970 BKJD → Sunspots/Solar Flares? Mean and STD respectively (periodogram): 22928.184e/s; 63.700e/s Notes: Periodogram and regular light curve have different fluxes despite the same quarter…why? Cataclysmic Variables or solar flares (CVs) causing spikes in normalized flux?

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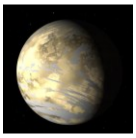
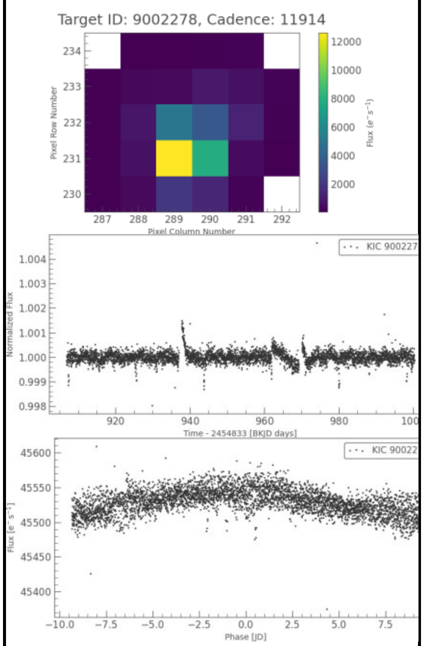
Table 1. (continued).

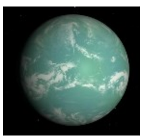
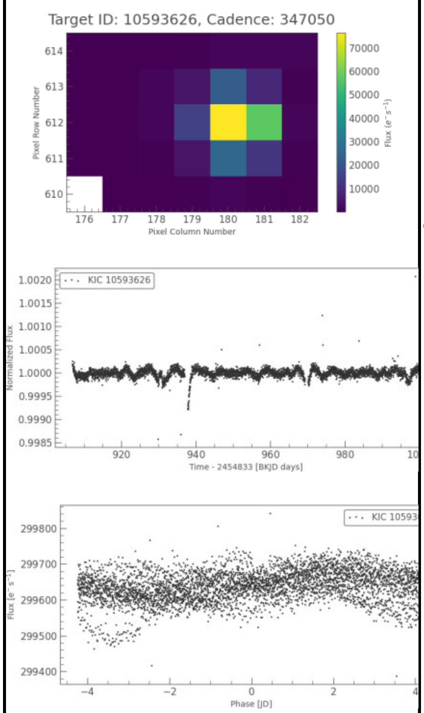
<table>
<tr><td>Kepler-62f KIC 9002278</td><td></td><td>
</td><td>Period: ~ 18.68029256259906 d

<u>Quarter: 10</u>

Peak Analysis: Uniform peak at epoch

Gaps: ~937 BKJD, ~962 BKJD, ~970 BKJD → Sunspots/Solar Flares?

Mean and STD respectively (periodogram): 45529.16015625e/s; 17.55561637878418e/s

Notes: Surprisingly streamline normalized flux. Cataclysmic flares at gaps?</td></tr>
<tr><td>Kepler-22b KIC 10593626</td><td></td><td>
</td><td>Period: ~ 8.491103135861605 d

<u>Quarter: 10</u>

Peak Analysis: Uniform peak at ~ JD = 2

Gaps: ~937 BKJD, ~969 BKJD → Sunspots/Solar Flares?

Mean and STD respectively (periodogram): 299638.59375e/s; 43.67795181274414e/s

Notes:
Gaps cause a decrease in flux → cannot be solar flares or CVs, so they must be sunspots or another effect that lowers flux

One interesting thing is that the gaps appear to all be at the same time for all exoplanets so far..</td></tr>
</table>

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Table 1. (continued).

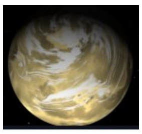
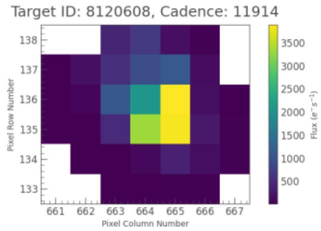
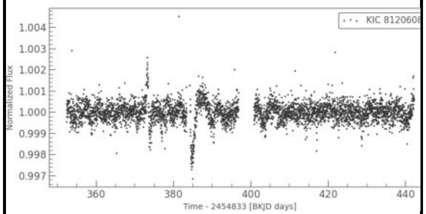
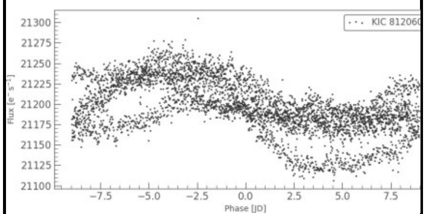
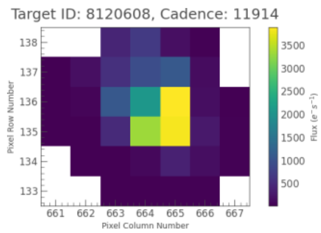
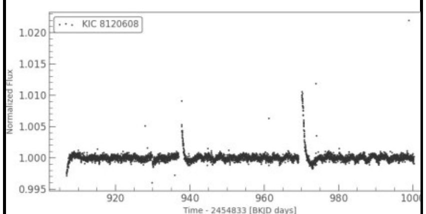
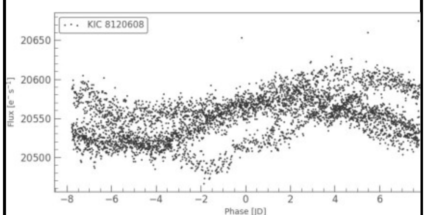
Kepler-186f KIC 8120608		      	Quarter 4: Period: ~ 17.96099556835252 d Peak Analysis: Uniform peak at ~ JD = -5 and JD= 5 Gaps: ~375 BKJD, ~385 BKJD, ~395 BKJD → Sunspots/Solar Flares? Mean and STD respectively (periodogram): 21197.08984375e/s; 32.141685485839844e/s Notes: Extremely long gap at ~395 JD possibly due to an elongated solar flare or sunspots (slow rotational period)? Periodogram shows two different curves with different peaks → potential for binary star system? (confirmed singular star system) Quarter 10: Period: ~ 15.567148956484743 d Peak Analysis: Uniform peak at ~ JD = -2 and JD = 4 Gaps: ~937 BKJD, ~969 BKJD → Sunspots/Solar Flares? Mean and STD respectively (periodogram): 20551.994140625e/s; 28.273418426513672 e/s Notes: Periodogram shows two different curves with different peaks → potential for binary star system? (Confirmed to be singular star system)

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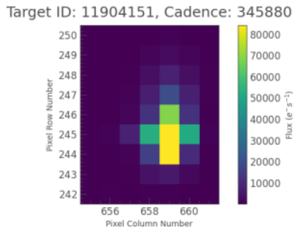
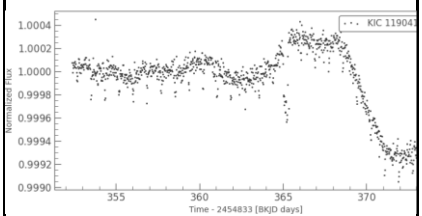
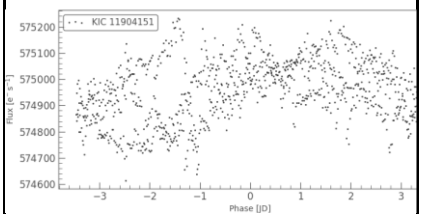
Table 1. (continued).

			*Quarter = 10 has the same gaps at every point of time in every exoplanet observed - possibly an error with the Kepler telescope itself? Cataclysmic flares at gaps?
Kepler-10b KIC 11904151		  	Period: 6.940502575067512 d Quarter 4: Peak Analysis: Uniform peak at ~ JD = -2 and JD = 2 Gaps: ~364 BKJD → Sunspots/Solar Flares? Mean and STD respectively (periodogram): 574957.6875e/s; 78567504882812e/s Notes: *Normalized flux curve shows drastic decrease in flux starting at ~360 BJKD, why?

3. Conclusion

The overarching goal was to analyze light curve data from stars in planetary systems that harbor terrestrial exoplanets. As seen in Table 1, the period for each star ranges from approximately 6 to 19 days based on the periodograms. Additionally, the highest observed brightness (flux) out of the systems analyzed was approximately 570,000 e/s. Surprisingly, gaps can be seen at approximately 937 BKJD and 970 BKJD on all quarter 10 graphs for each exoplanet. Since these gaps occur among all stars, the cause was likely a temporary error with the Kepler telescope. All in all, this paper demonstrates that astronomical data is abundant and easily accessible to the general public, and analyzing that data is made simple with the publicly available NASA Exoplanet Catalog and the Lightkurve package.

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