AP4 Transiting Extrasolar Planets

Transit Method in Exoplanet Detection

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Abstract

In a universe with many stars and potentially even more planets, the hunt for worlds much like our own has always sparked curiosity in people. This project leverages the Transiting Exoplanet Survey Satellite (TESS) data to work its way through the cosmic noise and find the subtle dimming of light caused by exoplanets as they pass in front of their host stars. Through the process of data acquisition and analysis using Lightkurve and the Box Least Squares algorithm, we have identified three promising exoplanet candidates TIC 44792534, TIC 460205581, TIC 207468071 and a potential Tri-Planetary System, showcasing the diversity in size, temperature, and orbital periods. These findings, while offering a glimpse into the vast planetary diversity have instrumental challenges and observational anomalies posing significant challenges. Through this project we can show how to combat the challenges and push towards the finding of exoplanet candidates.

1. Introduction

NASA's Transiting Exoplanet Survey Satellite (TESS)[1] has made the once speculative realm of exoplanetary science into a domain of empirical discovery, identifying over 7138 exoplanet candidates. 432 confirmed[2]. Some of these worlds are giants, larger than Jupiter, and some are small, rocky bodies that could be like our Earth. I explore how TESS is unveiling a universe rich with planets and how, through this project, we are contributing to this era of discovery.

TESS, represents NASA's next step in the search for planets outside our solar system, known as exoplanets. Launched in 2018, TESS's primary mission is to survey the brightest stars near the Earth for transiting exoplanets, it employs four wide-field cameras to cover an area of sky 400 times larger than that monitored by the Kepler mission, aiming to capture phenomena such as planetary transits (events that occur when a planet passes in front of its star), resulting in a periodic and temporary dimming of the star's brightness. These transits provide valuable data, allowing us to find out the planet's size and orbit. TESS is building a catalogue of planets with precise locations, providing vital targets for future telescopes to study their atmospheres, compositions, and even signs of habitability.

The goal is not just to add numbers to the catalogue of known exoplanets but to deepen our understanding of the diversity and complexity of planetary systems beyond our own. By analysing the light curves (graphs that show the brightness of stars over time) we search for telltale dips in brightness that signify a planet passing in front of its host star. My work in data analysis and computational astrophysics help in understanding the exoplanet by finding the size and other parameters of the planet.

This project come with many questions like, what makes the discovery of new exoplanets so crucial, and why do we dedicate vast resources and technologies like TESS to this cause? Each new exoplanet discovered brings us closer to finding worlds that resemble our own. Furthermore, studying these diverse planetary systems provides data on how planets form and evolve, it helps us understand our own solar system better, and adds to the curiosity if we are alone in this world.

2. Method

2.1 Introduction to Methodology

In this project, a python program was created in Jupyter Notebook to automate the detection and analysis of exoplanets using data from TESS. The methodology employs the Python library Lightkurve[3], which provides specialized tools for analysing astronomical time-series data from space telescopes like TESS and Kepler. Utilizing Lightkurve's capabilities, the program used advanced algorithms and data processing techniques to identify potential exoplanets by analysing the light curves of stars. Central to my analysis is the Box Least Squares (BLS) algorithm[4], which searches for periodic dips in stellar brightness indicative of transiting exoplanets. By integrating all steps from data acquisition and preprocessing to analysis and validation into a single automated workflow, this helps with keeping the results to high precision of analysis.

2.2 Data Acquisition

For the analysis, light curve data was extracted from the TESS public archive in the Mikulski Archive for Space Telescopes (MAST)[5]. The light curves provide measurements of stellar brightness as a function of time, recorded every two minutes, thereby offering high-resolution temporal data necessary for detecting tiny changes in brightness. This high cadence data is crucial for identifying the transient events indicative of planetary transits.

2.3 Data Preprocessing

Preprocessing is one of the most important steps as it sets up the data to be analysed to a high precision. Given the nature of TESS light curve data, several preprocessing steps were rigorously employed to ensure that subsequent analyses was based on reliable and normalized datasets:

Normalization: Each light curve underwent a normalization process to ensure uniformity across all datasets. It involved scaling the brightness measurements to standardise the median flux value to 1. This normalization is essential for comparing changes in brightness consistently across different stars and observational periods, and being able to accurately identify relative flux decreases due to transits as seen in *Fig.1*
Outlier Removal: To enhance the signal-to-noise ratio and reduce the potential for false positives in transit detection, outliers were removed from the light curves. This process involved implementing a sigma-clipping algorithm, where data points exceeding six standard deviations (σ=6) from the median flux were excluded from the analysis. This threshold was chosen to balance genuine transit signals and eliminating data points likely caused by instrumental effects or cosmic ray impacts.
Flattening: The light curves was subjected to a flattening process, which is designed to remove any systematic trends that could mimic or hide planetary transits. This was a built in lightkurve tool, ensuring a consistent baseline. Flattening is significant in preserving the integrity of transit features while removing many types of system and steller variability as seen in *Fig.1*

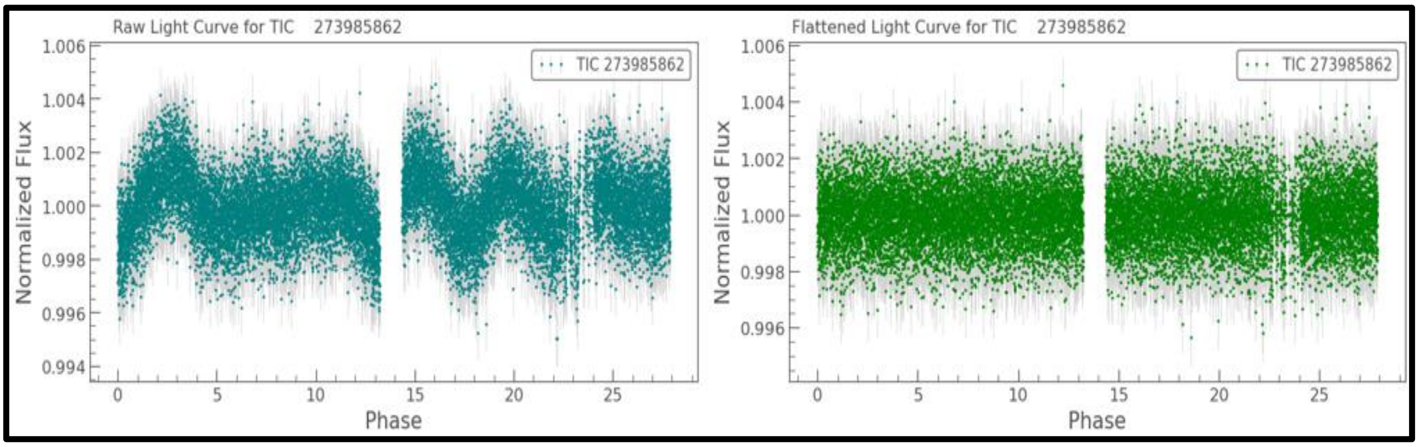


Fig.1: ***Light Curve Processing for TIC 273985862***. *On the left, the raw light curve data showing the star's flux variability normalized over time due to stellar activity and instrumental noise. On the right, the light curve is shown after the flattening process. Normalization adjusts the flux values to centre around 1, which allows for a consistent scale when comparing changes in brightness. Flattening is performed to remove the effects of stellar variability and instrumental trends, resulting in a cleaner signal that enhances the visibility of potential transit events.*

2.4 Transit Detection Technique

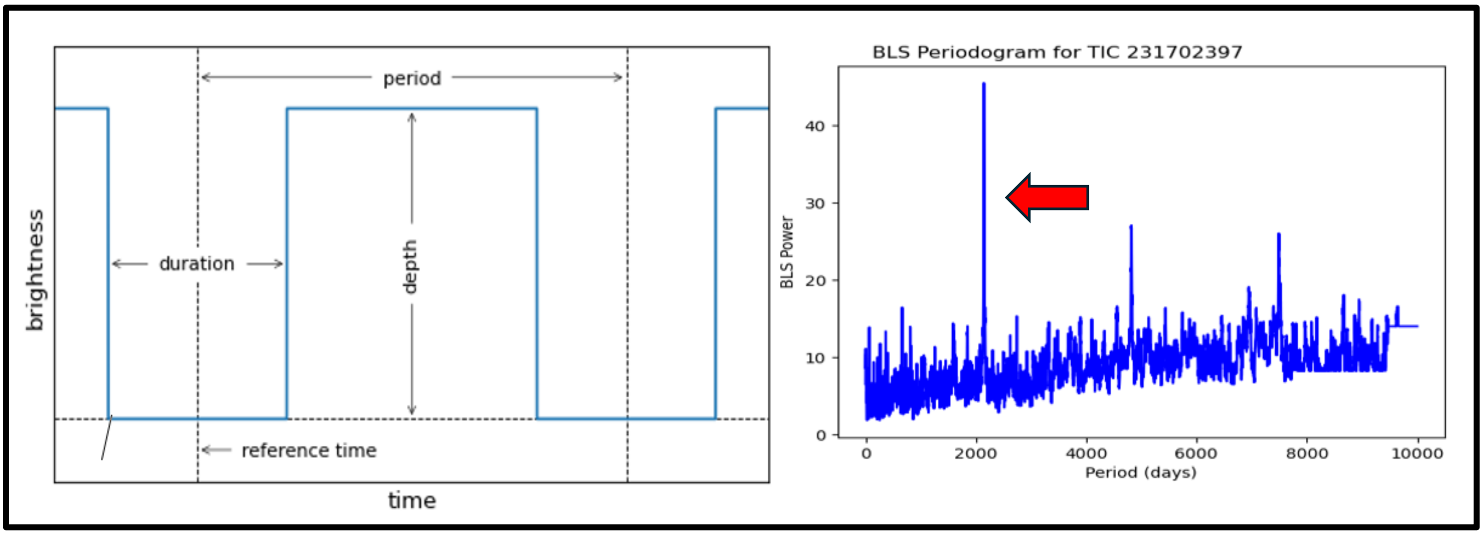
Detecting potential exoplanetary transits is the main goal of the analysis, only being able to do so from the capabilities of the **Lightkurve** Python package. The Box Least Squares (BLS) algorithm plays a big role in identifying the periodic and dimming events in stellar brightness indicative of planetary transits.

BLS Algorithm: BLS is designed to detect periodic, box-shaped dips in light curves (*Fig.3*), signatures of transiting exoplanets. BLS is applied to each light curve, the algorithm scans a range of periods and durations, computing a power spectrum to pinpoint the most likely periods characterized by significant transit signals. This computational approach ensures that the data found is accurate compared to doing it by eye.

Periodicity Search: To sort a broad spectrum of potential orbital periods, the BLS algorithm is configured to search within an interval from 0.5 days to 20 days. This range is chosen to include short period planets as well as those with more extended orbital periods, thus being able to see majority periods of viable planetary candidates.

Potential Transits (Phase Folding): Following the identifying of potential transits, the light curves are phase-folded at the detected periods. This step enhances the visibility of the transit's shape and depth, which is crucial for the validation and detailed characterization of the transit features like the transit depth. Phase folding aligns multiple transit events, showing the periodic signal against random fluctuations.

Visual Representation: An illustrative figure of a BLS periodogram (*Fig.4*) will demonstrate how the algorithm can see between genuine planetary signals and instrumental variations. This visual aid is important for understanding underlying principles of the BLS method and its effectiveness in our analysis.



[6]**Fig.2/3: *Illustration of Transit Features and BLS Periodogram Analysis for TIC 231702397 Left:*** *A schematic representation of the box least squares method. The 'depth' corresponds to the fractional decrease in stellar brightness during the transit, 'duration' indicates the time taken for the planet to traverse the star's disk, and 'period' represents the time between consecutive transits. 'Reference time' denotes a fixed point in time, typically the midpoint of the first detected transit.* ***Right:*** *The BLS periodogram for TIC 231702397, displays the detection power as a function of the period. The peak (red arrow) signifies the most likely period at which transit events occur, suggesting the potential orbital period of an exoplanet around the host star.*

2.5 Signal Analysis

Signal analysis is done to authenticate the periodic of the light curve and be able to know if it's a potential candidate or just random noise.

Periodicity: The first step in analysing the signal is to check if it appears at regular intervals. Lightkurve is used to line up the data from multiple orbits to see if the dips in brightness happen consistently and match up well across different cycles, first checked by eye then using bls computationally if it is not easy to see the consistent patterns by eye, these are key indicators of planets passing in front of their stars.
Variability and Noise: Critical to our analysis is the differentiation of genuine planetary transits from both intrinsic stellar variability, such as stellar flares or pulsations, and noise. We closely examine the noise patterns in the light curves and cross reference to stellar phenomena found on the MAST website.
Bootstrap Technique: The final step involves using statistical methods, especially one called the bootstrap technique. This method helps test the reliability of the findings by simulating different scenarios using the data. It shuffles the light curve data and reassess the transit signals to see how likely it is that the patterns we observe could be due to chance rather than actual planetary transits.

2.6 Verification and Validation (False Positives [7])

Verification and validation are crucial, ensuring that the transit signals identified are actual exoplanetary bodies rather than artifacts or false positives caused by stellar dynamics or instrumental noise. To achieve this, additional astrophysical data points were meticulously examined:
Centroid Analysis: During transit events, the apparent centre of the star's brightness should remain stable unless affected by another astronomical object, such as a background star. Analysing the centroid motion data from TESS confirms that the dimming events are associated with the target star.
Secondary Eclipse Observation: The presence of a secondary eclipse, when the planet passes behind the star, is a confirming feature of a true planet.
Symmetry Assessment: A genuine planetary transit exhibits a characteristic symmetry in the light curve, whereas phenomena such as eclipsing binaries often result in asymmetrical light curves.

2.6 Parameter Estimation

Once potential exoplanets were validated and confirmed through our verification process, planetary parameters proceeded to be estimated. These parameters are crucial for characterizing the physical and orbital properties of the exoplanets.

2.6.1 Stellar Parameter Acquisition

Before estimating exoplanetary parameters, necessary stellar data was first compiled as seen in *Table.1*, which are needed for multiple calculations. This information was programmatically accessed and inputted into the analysis through the ***astroquery.mast*** python module, which with the Mikulski Archive for Space Telescopes (MAST).

The integration of ***astroquery.mast*** facilitated the import of accurate stellar parameters, which are crucial for the calculation of planetary radii, orbital semi-major axes, and equilibrium temperatures. Ensuring the integrity of this data is important as it sets up the rest of planetary calculations.

Catalog of Steller parameters for TIC 44792534

Parameter	Value
Star's Name	44792534
Radius (R⊙)	1.93 ± 0.10
Mass (M ⊙)	1.03 ± 0.13
Metallicity [Fe/H]	N/A
Surface Gravity log(g)	3.88 ± 0.07
Effective Temperature (Teff)	5756 ± 127 K
V-band Magnitude	9.77919
K-band Magnitude	8.779
Right Ascension (RA)	61.9410862289005
Declination (Dec)	-25.2086752996127
Distance (parsecs)	238.77 ± 1.89

Table 1: *Catalog of Stellar Parameters for TIC 44792534. The table summarizes the fundamental astrophysical properties of the target star observed by TESS*, data from the Mikulski Archive for Space Telescopes (MAST).

2.6.2 Radius

To derive the planetary radius (***Rp***), the transit depth (***Δ***) is obtained from the phase-folded light curve. The transit depth is represented as:

$$\Delta = \left(\frac{R_p}{R_*}\right)^2 \qquad \textbf{\textit{Eqn.1}}$$

Where ***R∗*** is the stellar radius. The depth ***Δ*** measured from the phase-folded light curve by averaging the normalized flux during the transit and comparing it to the out-of-transit baseline. Once ***Δ*** is ascertained, ***Rp*** is computed as:

$$R_p = R_*\sqrt{\Delta} \qquad \textbf{\textit{Eqn.2}}$$

The accuracy of this estimate relies on precise measurements of ***Δ*** and ***R∗***. The resultant planetary radius can be presented in Earth radii (R⨁) or Jupiter radii (R_J), which is often preferred for several reasons when describing gas giants or large exoplanets: Jupiter is the largest planet in our solar system, and its radius provides a more better scale for giant exoplanets, which is particularly useful when the planets being described are of a size comparable to or larger than Jupiter itself.

2.6.3 Equilibrium Temperature

The equilibrium temperature (**Teq**) of the planet is an essential parameter for understanding its potential habitability. It is estimated using the formula:

$$T_{eq} = T_* \sqrt{\frac{R_*}{2a}} \quad \textit{Eqn.3}$$

Where ***T∗*** is the effective temperature of the host star and ***a*** is the semi-major axis of the planet's orbit. This calculation assumes a bond albedo of zero (no reflectance) and perfect heat redistribution across the planet's surface. By setting the bond albedo to zero, it's assumed that the planet absorbs all the incident radiation from its star and reflects none. This simplification makes it possible to estimate ***Teq*** without detailed knowledge of the planet's atmospheric composition or surface properties, which are often unknown for exoplanets. Perfect heat redistribution assumes that the planet is efficiently transfers heat from the day side to the night side, resulting in a uniform temperature across its surface. While at the same time, this idealization simplifies the calculation by not requiring details about the planet's atmospheric dynamics or rotation rate.

2.6.4 Orbital Period

The orbital period (***P***) is determined by analysing the timing of transits. The initial estimate from the Box Least Squares (BLS) algorithm is refined by fitting a transit light curve model to the observed data, optimizing to minimize residuals. The period P is given by *Eqn.4*, where ***f*** is the frequency of the transit signal identified by the BLS algorithm.

$$P = \frac{1}{f} \quad \textit{Eqn.4}$$

2.6.5 Semi-major Axis

The semi-major axis of an exoplanet's orbit is a fundamental parameter that describes the size of the orbit. It is derived using Kepler's Third Law, which relates the orbital period of a planet to its semi-major axis, in conjunction with Newton's Law of Gravitation. The equation for the semi-major axis ***a***, in astronomical units (AU), given the orbital period ***P***, in years, and the mass of the star ***M****, in solar masses, is:

$$a^3 = \frac{G(M_* + M_p)P^2}{4\pi^2} \quad \textbf{\textit{Eqn.5}}$$

Where ***G*** is the gravitational constant, however, the mass of the planet ***Mp*** is usually several orders of magnitude smaller than that of the star ***M****, especially when dealing with stars like or larger than our Sun, and even more so for Earth-like or Neptune-like planets. In such cases, ***Mp*** becomes negligible in the equation:

$$a^3 \approx \frac{GM_*P^2}{4\pi^2} \quad \textbf{\textit{Eqn.6}}$$

For practical applications, when ***P*** is known (usually in days) and we are working with a star of known mass ***M****, the equation is often recast in terms of days for ***P*** and solar masses for ***M**** to compute ***a*** in astronomical units directly:

$$a = \left(\frac{GP^2}{4\pi^2}\right)^{1/3} \left(\frac{1}{M_*}\right)^{1/3} \quad \textbf{\textit{Eqn.7}}$$

The gravitational constant ***G*** and the factor $\frac{4\pi^2}{G}$ are sometimes replaced by a proportionality constant derived from observational data within our solar system, where the semi-major axis and orbital period of the planets are well known.

The estimation of ***a*** provides insight into the possible climate of the planet since it directly influences the amount of radiation received from the star.

2.6.6 Transit Duration

In our analysis pipeline, the transit duration (***T_d****)* is extracted algorithmically from the phase-folded light curve. ***T_d*** is determined by measuring the width of the transit event at a specific depth, typically the full-width half-maximum of the transit dip. This is the point where the light curve begins to descend as the planet starts its transit until it ascends back to full brightness as the planet completes its transit.

2.7 Error Analysis

Stellar Parameter Uncertainties

The uncertainties in stellar parameters were derived from the data provided by the TESS Input Catalog (TIC) accessed via the **astroquery.mast** Catalogues module. These parameters come with pre-calculated errors based on extensive photometric and spectroscopic measurements.

For instance, the uncertainty in the stellar radius and mass are used to calculate the errors for the planetary parameters. They can be used to calculate uncertainties for the planet's radius and semi major axis and equilibrium temp.

Bootstrap Analysis for Planetary Parameters

For planetary parameters that are not a direct retrieval from the TIC, such as the orbital period, transit epoch, duration, and depth, we employed bootstrap analysis to estimate their uncertainties. This statistical technique involves repeatedly resampling the dataset and recalculating the parameter of interest to form a distribution of possible values.

The bootstrap method provides a way to understand the variability in our measurements and offers a percentile-based confidence interval for the parameters. The 68% confidence interval, analogous to the 1σ standard deviation for a Gaussian distribution, is then determined by finding the range within which 68% of the bootstrapped parameter values lie. This interval is taken to represent the uncertainty in the parameter measurement.

This technique is powerful as it makes minimal assumptions about the underlying statistical distribution of the data and is well-suited for the often-non-Gaussian distributions found in exoplanet transit data. It accounts for random errors inherent in the observational data but does not address potential systematic errors that could arise from the models or assumptions used.

In addition to individual uncertainties for instance, the transit depth and duration are both derived from the transit light curve and may be affected by noise, such as stellar activity or instrumental effects. This noise is addressed by the bootstrap method, which preserves these in the uncertainty estimates by resampling the entire light curve.

3. Observations and Results

3.1 Overview

This section presents the observational data and results derived from the analysis of TESS light curves for three selected Target Input Catalog (TIC) objects, a potential multi planetary system and other diverse stellar phenomena. The data illustrates the diversity and richness of planetary systems surveyed by TESS. Each subsection details the stellar parameters, the preprocessing methodology applied to the light curve data, and the outcomes of the transit analysis, including potential exoplanet candidate characteristics.

3.1 Diverse Steller Phenomena

Within all the of photometric data procured by TESS, many intrinsic stellar variabilities present both an observational challenge and an opportunity for astrophysical insights. The recognising and characterising these phenomena are critical for detangling planetary signals from stellar noise.

3.1.1 Stellar Spots/Sunspots(fig.4): Stellar spots are akin to sunspots but on other stars. They are cooler, darker regions on the stellar surface caused by magnetic field concentrations. As a star rotates, these spots can cause quasi-periodic fluctuations in the light curve because the spots alter the amount of light emitted from the star. The regularity of these fluctuations can provide the stars rotational period and can sometimes be mistaken for or obscure the transits of small exoplanets.

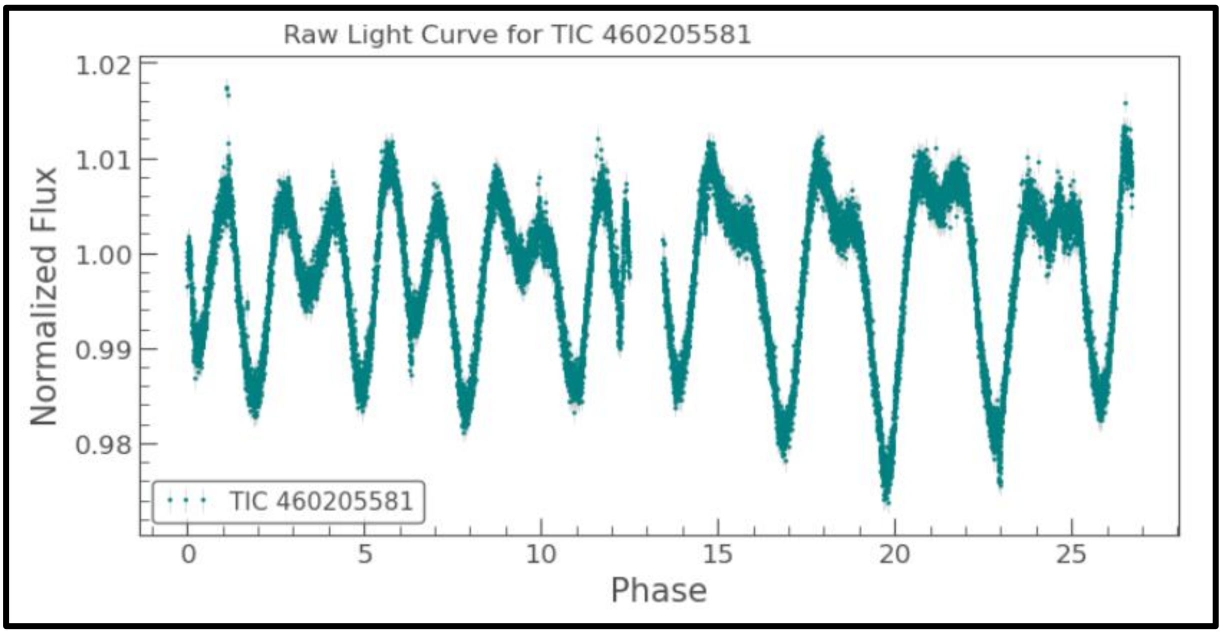


Fig 4: ***Raw Light Curve Demonstrating Stellar Photometric Variability due to Spots*** This graph exhibits the normalized flux from TIC 460205581, displaying distinct, quasi-periodic brightness fluctuations due to stellar spots. The cyclical pattern of dimming and brightening aligns with the star's rotational phase, revealing the presence of cooler, magnetically active regions on the stellar surface.

3.1.2 Eclipsing Binaries(fig.5): Eclipsing binaries are systems where two stars orbit each other so that they periodically eclipse one another from our point of view. These eclipses cause dips in the light curve that are typically much deeper than those caused by transiting exoplanets. The shape, timing, and duration of these dips can tell us much about the nature of the binary stars, including their sizes, orbital periods, and even potential mass ratios.

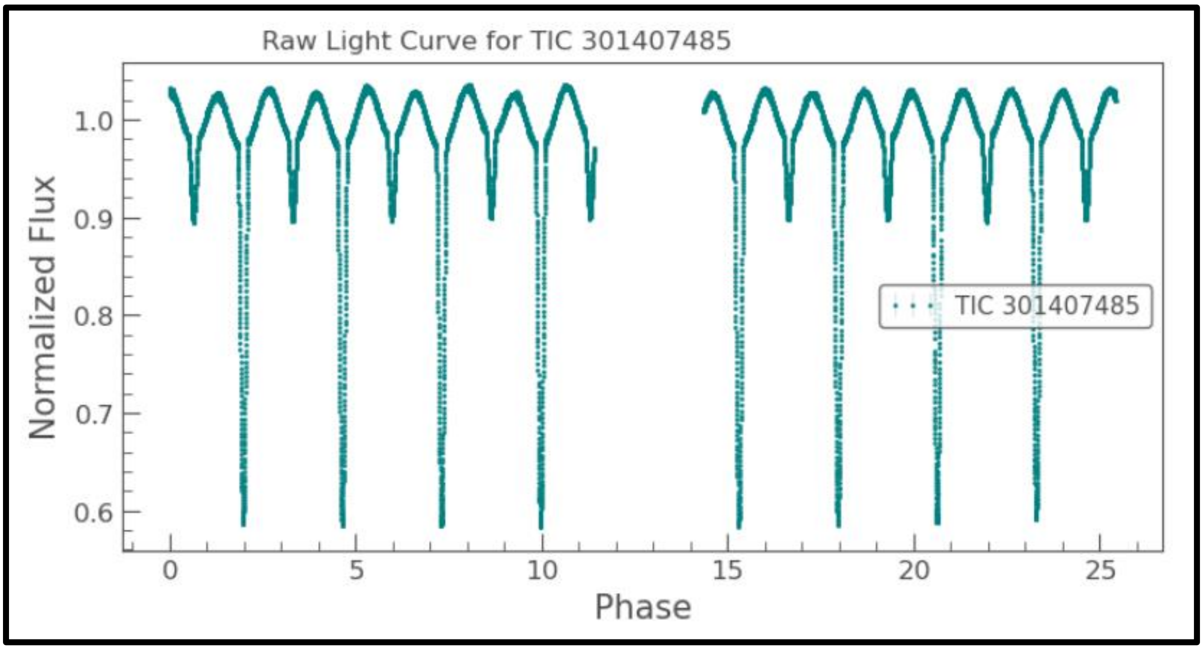


Fig.5: ***Raw Light Curve of TIC 301047485 Indicating Eclipsing Binary Dynamics:*** This plot presents the raw data, characterised by pronounced and regular eclipsing events. The light curve's deep and symmetrical troughs indicate a binary star system, where two stars periodically pass in front of each other from our vantage point.

3.1.3 Solar Flares(fig.6): Solar flares are sudden, intense outbursts of electromagnetic radiation from a star, including our Sun. In light curves, they manifest as brief, sharp increases in brightness. They indicate magnetic activity that could have significant implications for the habitability of orbiting exoplanets. The frequency and magnitude of flares can also inform us about the age and magnetic environment of the host star.

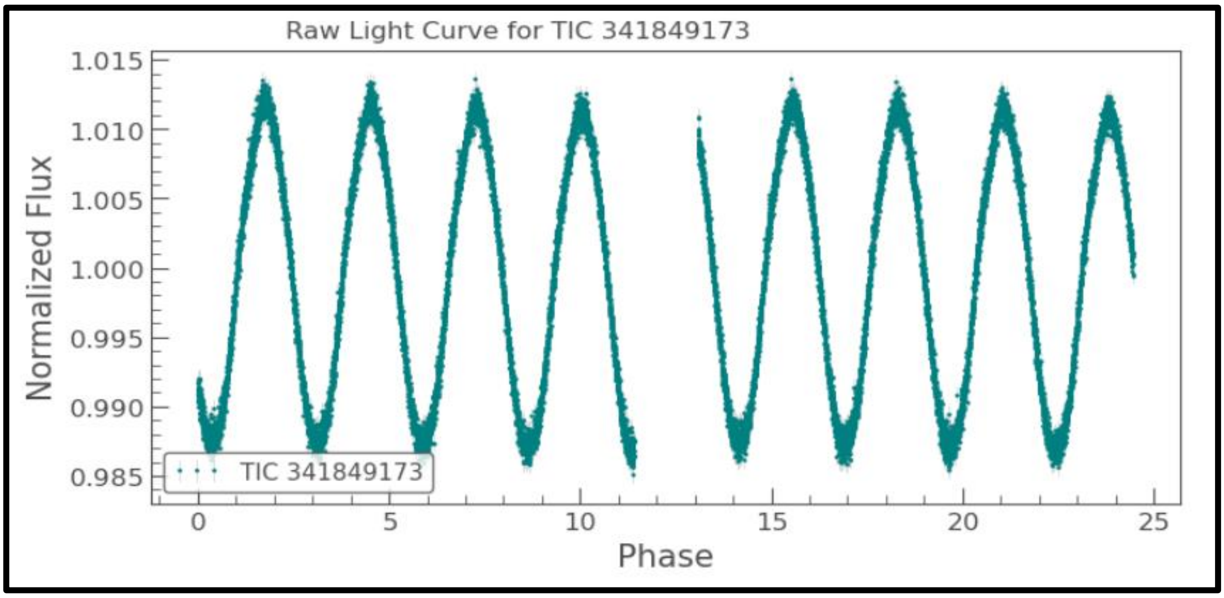


Fig.6***: Raw Light Curve for TIC 384198173 Showcasing Stellar Flare Activity:*** Depicted here is punctuated by sharp, episodic peaks superimposed upon the flux, characteristic of stellar flares. These abrupt enhancements in luminosity are symptomatic of intense magnetic activity, often correlated with the release of high-energy particles.

3.2 Planet Candidates

Candidate 1: TIC 44792534

Sec 31, P= 3.68d, Rp= 0.8747 R_J

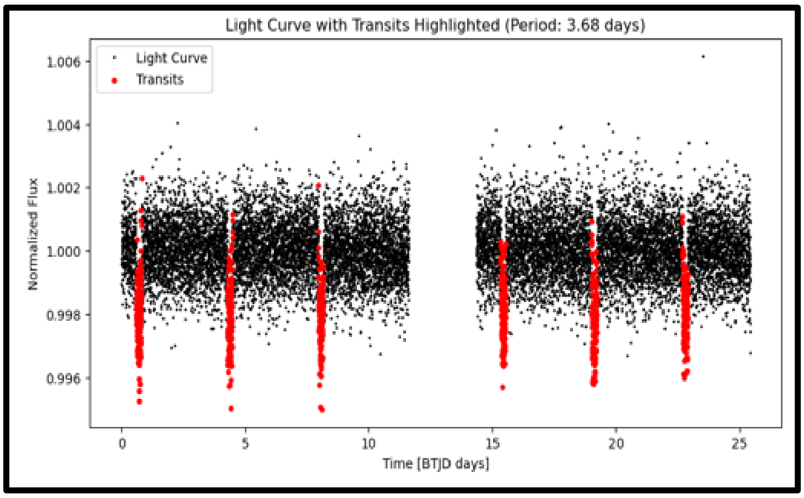


Fig.7: ***Light Curve with Marked Transits:*** *Normalized flux of TIC 44792534 over time, showcasing marked transits. The periodic dimming indicated by red marks aligns with an orbital period of approximately 3.68 days, suggesting the presence of*

Validating Candidate 1: TIC 44792534

TIC 44792534, as a potential exoplanet is built upon a rigorous analysis of its transit signatures the photometric evidence, characterized by periodic and consistent telltale signs in the light curve, strongly points to the regular passings in front of the host star. The uniformity of the transit depth across multiple events, as illustrated in Fig.*7* of the light curve, is indicative of a singular object with consistent physical dimensions. The transit depths in the light curve all being the same size shows great progress in proving the exoplanet as it can't be erratic stellar variability.

The BLS periodogram (*Fig.8*), shows a clear peak at 3.68 days, which matches the observed transits' frequency. The sharpness and isolation of this peak further rules out the likelihood of false positives caused by phenomena such as pulsations or stellar activity. *Fig.9* presents the phase-folded light curve of the candidate exoplanet, where the transits are superimposed to reveal a clear and repeated pattern. The resulting transit duration and depth, taken in conjunction with the host star's known properties, allow for the estimation of the candidate's size, leading to a calculated radius of 0.8747 R_J, within the range expected for a gas giant exoplanet, with a transit duration of 4.8 hours.

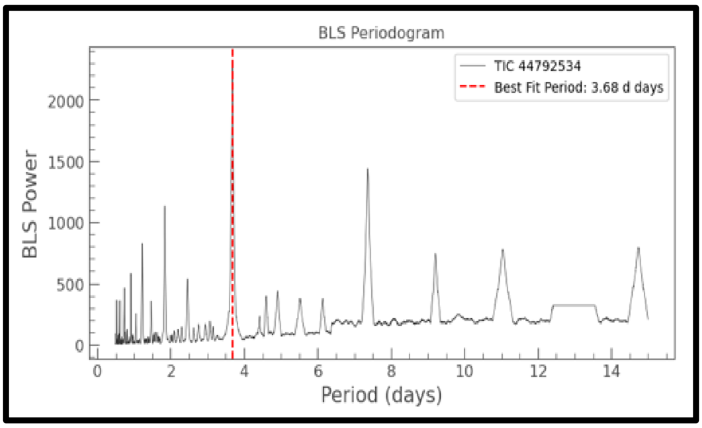


Fig.8: ***BLS periodogram for TIC 44792534****, highlights the strongest signal at approximately 3.68 days.*

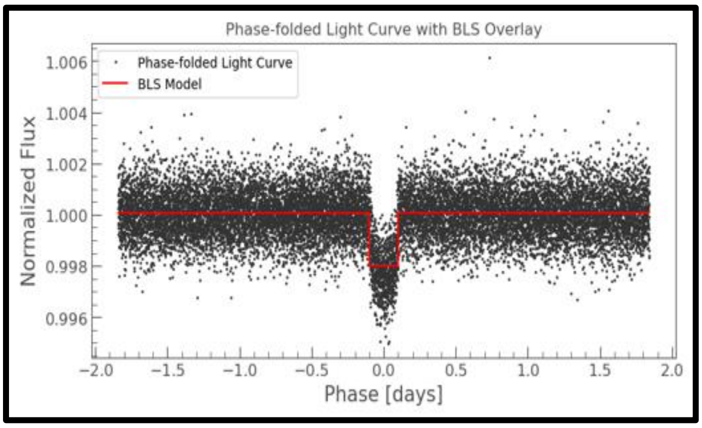


Fig.9: ***Phase-folded Light Curve with BLS Model Overlay:*** *This is the phase-folded light curve with a period of approximately 3.68 days.*

Observational Anomalies and Data Resilience [8]**:** Observational anomalies, such as star tracker malfunctions and scattered light issues, compromised data integrity during the collection period in Sector 31. Despite these challenges, including operational limitations to Camera 1, the detection of transits remained robust. These interruptions did not stray from the successful identification of a candidate exoplanet, as subsequent data resumption in Sector 32 mitigated the impact of these gaps, so in summary, the convergence of consistent transit depth, periodogram analysis, and phase-folding techniques provides a compelling case for the candidacy of TIC 44792534 as an exoplanet.

<u>Candidate 2: TIC 460205581</u>

Sec 38, P= 8.323 d, Rp= 0.296 R_J

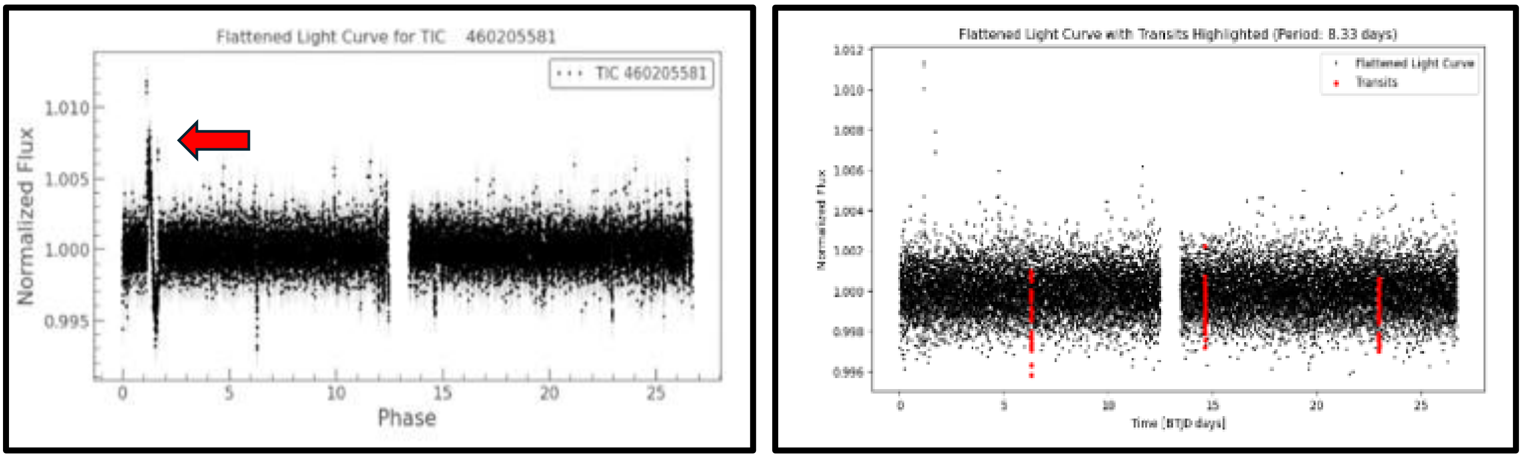


Fig.10/11*: Flattened Light Curve:* *(Left) The normalized and flattened light curve of TIC 460205581, illustrates variability and an isolated flare event (red arrow), evidenced by a sharp increase in flux. (Right) The same with the stellar flare removed. The periodic dimming indicated by red marks every 8.33 days.*

At the beginning of the analysis the raw light curve presented a challenge, it showed periodic brightness fluctuations due to stellar spots. These fluctuations, evident before any data processing, showed the star's rotational period and complicated the transit detection, as they could be mistaken for signals from orbiting bodies (*Fig.5*), its detected orbital period was 2.98 days.

Upon flattening the light curve to normalize these stellar variations, a flare (a brief, intense spike in luminosity) was able to be seen in the light curve, these brief events are important for figuring out what's happening with stars, but it can be tricky to tell the difference between a planet passing by from stellar phenomena (*Fig.10*). The BLS periodogram analysis of the flattened data revealed a well-defined peak at 8.33 days (*Fig.12*), indicative of a genuine transit event and likely signalling the presence of an exoplanet.

The phase-folded light curve (*Fig.13*) further corroborated this finding, where the transits' repeatability and consistency were visually represented. Even with some confusion from spots on the star, the pattern was clear, pointing to a strong possibility of a planet being there.

The estimated radius of the exoplanet, derived from the transit depth, came out to be 1.21 ± 0.21 Jupiter radii. This measure falls within the expected range for gas giant exoplanets. The radius estimation, combined with the period and transit duration derived from the phase-fold provides a well put together candidate profile. Considering the TESS Data Release Notes[8] for Sector 38, which details the observational let downs such as scattered light and calibration issues, the clarity of the transit signal for TIC 460205581 is good.

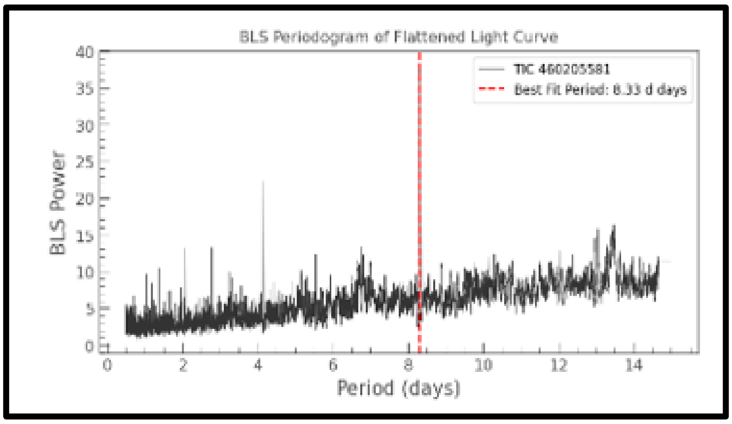


Fig.12: ***BLS periodogram for TIC 44792534***, *highlighting the strongest signal at a period of approximately 8.33 days.*

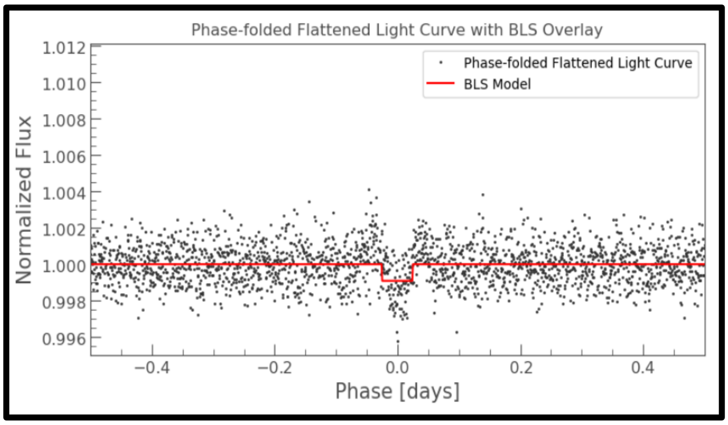


Fig.13: ***Phase-folded Light Curve with BLS Model Overlay:*** *This is the phase-folded light curve at an 8.33-day period with a BLS model fit where u can see a small dip in flux*

Candidate 3: TIC 207468071

Sec 23, P= 20.382 d, Rp= 0.7.578 R_J

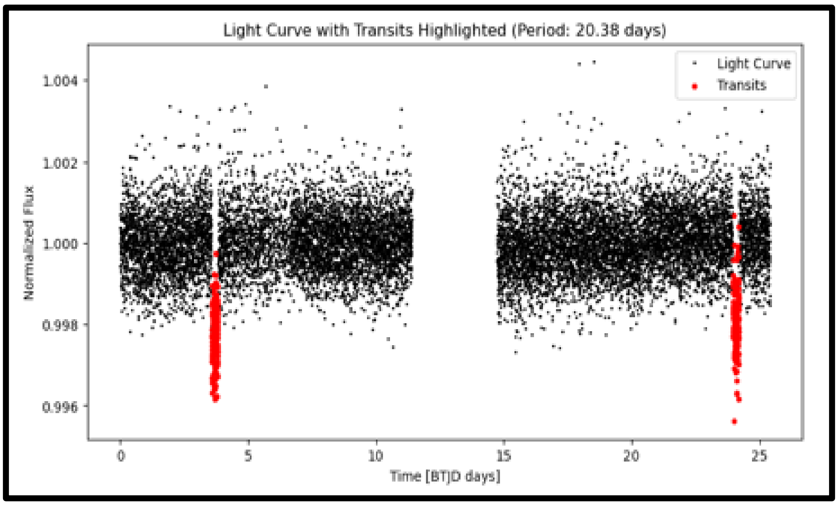


Fig.14: ***Light Curve with Marked Transits:*** *Normalized flux of TIC 207468071 over time, showcasing marked transits. The periodic dimming indicated by red marks aligns with an orbital period of approximately 20.38 days, suggesting the presence of a transiting exoplanet.*

During the transit detection process for TIC 207468071 caught the attention to be a compelling candidate due to its unique transit signature. The light curve initially revealed periodic dimming events at a frequency that suggested a period of roughly half of the expected orbital duration. This initial finding within the 20-day observation showed that the program might have to be changed look outside the 20-day period to find the true transit, that can clearly be seen by eye.

A closer look at the light curve and BLS periodogram showed a significant peak at this half-period mark. This could mean many things, potentially there are secondary eclipses, or it could indicate a system with more than one celestial body it could even be a moon. To make sure we get the right orbital period of the exoplanet we looked further than 20 days so a longer period matching with the full orbit instead of half.

This adjustment to a total period of 20.38 days, aligns the transits into a periodic sequence that we could see by eye in the light curve. The phase-folded light curve, modelled over this doubled period, presented a clear and consistent signal, the estimated radius of the exoplanet, was determined to be 0.73 ± 0.218 Jupiter radii, enhancing our confidence in the candidate's validity.

The instrumental challenges noted in TESS Data Release Notes[8] for the sector in question. The robust transit sequence remained intact despite potential perturbations such as Earth's shadow passage and scattered light, which often obscure or distort transit signals,

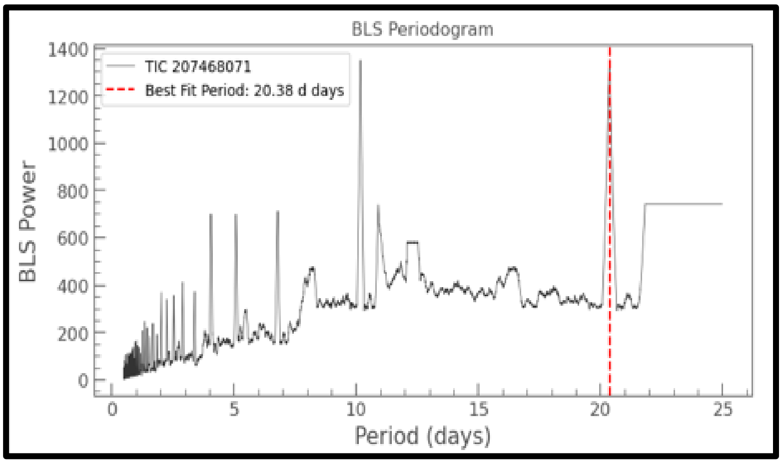


Fig.15: ***BLS periodogram for TIC 44792534***, *highlights the strongest signal at approximately 20.38 days.*

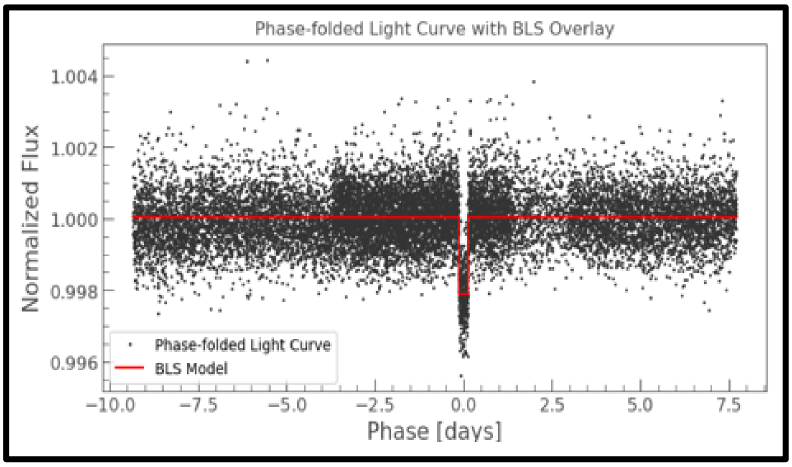


Fig.15: ***Phase-folded Light Curve with BLS Model Overlay:*** *This is the phase-folded light curve with a BLS model fit over a 20.38-day period.*

3.3 Overview of Candidates Parameters 1-3

Candidate 1: TIC 44792534 is characterized as a substantial exoplanetary body with a radius of approximately 0.875 Jupiter radii, indicating a sizeable gas giant. This planet orbits its host star, which is 1.93 solar radii in size, making the planet quite significant in comparison. The calculated equilibrium temperature of this candidate is notably high at 1777 K, suggesting a close orbital distance to the star, consistent with the semi-major axis measurement of approximately 0.0471 AU. The planet completes its orbit every 3.683 days, a relatively short period which, along with the equilibrium temperature, classifies it as a "Hot Jupiter."

Overview of Parameters of Candidates 1-3

TIC	44792534	460205581	207468071
Radius (Rj)	0.875 ±0.476	1.21 ±0.21	0.73 ±0.218
Equilibrium Temperature (K)	1777.238 ±123.97	1017.815 ±75.83	983.45 ±76.75
Period (days)	3.683 ±0.0013	8.32 ±0.0029	20.252 ±0.014
Transit Duration (hours)	4.8	1.2	5.76
Transit Depth (%)	0.288	0.287	0.225
Semi-major Axis (AU)	0.0471 ±0.0057	0.084 ±0.011	0.157 ±0.022

Table 2*: Parameters of Exoplanet candidates and their errors.* Each candidate exhibits its unique signature, providing a broadened perspective of the system's dynamical complexity and potential habitability scenarios.

The transit duration of 4.8 hours and a transit depth of 0.288% are matched with the expectations for a planet of this type. This further supported by the star's parameters, which include a mass of approximately 1.03 solar masses and an effective temperature conducive to planetary detection at 5756 K, and the star's surface gravity at log(g) 3.88 supports the stability of the transiting body's orbital dynamics. TIC 44792534 emerges as a strong candidate for a Hot Jupiter exoplanet, with consistent parameters and a clear transit signature.

Candidate 2: **TIC 460205581**, observes an intriguing candidate planet orbiting its host star. The light curve analysis suggests a potential gas giant planet based on its radius of approximately 1.21 ± 0.21 Jupiter radii. The equilibrium temperature is calculated to be 1017.815 ± 75.83 Kelvin, which, together with its orbital period of 8.32 ± 0.0029 days, points towards a warm exoplanet. The planet's transit depth calculated to be 0.287%, indicating a substantial decrease in stellar brightness during transit events, which is consistent with the expected transit depth for a gas giant. The calculated semi-major axis of 0.084 ± 0.011 AU indicates a close orbit around the host star, typical for many hot Jupiter's found by transit surveys.

The host star that the planet is transiting around has a radius of 1.01 ± 0.04 solar radii and a mass of 1.15 ± 0.16 solar masses, not far off the size of our own sun. The transiting exoplanets size and temp make it a strong candidate for further analysis into its atmosphere to check for habitability.

Candidate 3: **TIC 207468071,** the periodic dimming of light captured by the TESS observations indicates a planet with an estimated radius of 0.73 ± 0.218 Jupiter radii. The orbital period was found 20.38 this is then found to show the equilibrium temperature to be 983.45 ± 76.75 Kelvin, this suggests it is cooler than hot Jupiter's. With a transit depth of 0.225%, this is a decent drop in brightness that can tell us it's a sizeable planet. This size suggests the planet could be a smaller gas giant or a larger terrestrial planet. The semi-major axis 0.157 ± 0.022 AU places the planet in a potentially habitable zone, especially if greenhouse effects are considered.

The host star of this exoplanet candidate, with a radius of 1.62 ± 0.07 solar radii and a mass of 1.26 ± 0.18 solar masses, larger and more massive than our Sun. This kind of star can offer a different environment for planet formation than Sun-like stars. Overall, TIC 207468071 presents a good case of a candidate exoplanet. The having to adjust of the period past the 20-day search and the observational challenges of Sec 23 should push this candidate for furthermore detailed analysis.

3.4 Potential Tri-Planetary System (TIC 307210830)

The identification and characterising of these planetary candidates were achieved through analysis that involved masking planetary signals. The process involved carefully removing the primary transit signal, this allowed the detection of the next most periodic signal, which helped find other planetary bodies, whether it be stellar phenomena or a simple asteroid. By using this method on different TIC's I was able to find many different types of observed phenomena one being able to remove a solar flare that was in the way of my data in candidate 2 seen in *Fig.10* The appendix has a more comprehensive record of the periodogram and phase-folded light curve analyses, so we are able to see the full picture of this Tri-Planetary System.

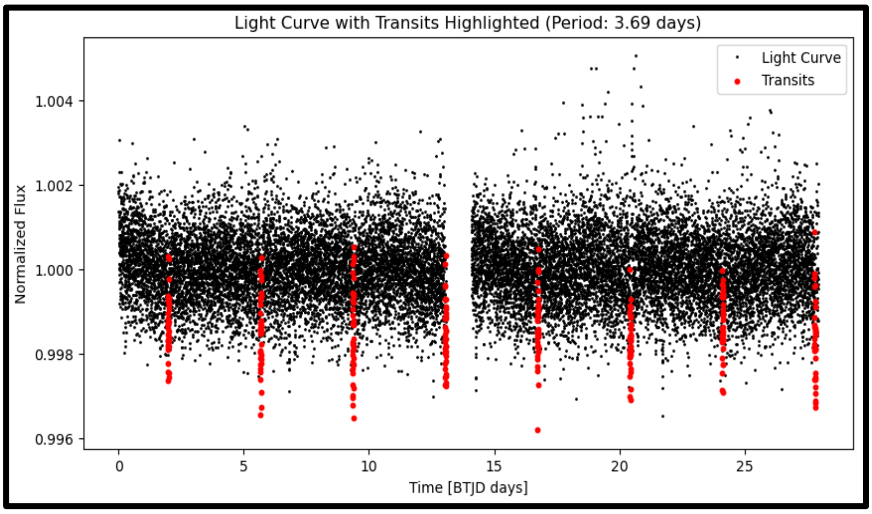


Fig.16*: Light Curve for Planet 1:* *Regularly spaced transits marked in red suggest an exoplanet orbiting every 3.69 days.*

3.4.1 Tri-planetary System: Primary Planet

TIC 301072810's second potential exoplanet: The light curve of TIC 301072810 showcases potential transits of a quite a large gas giant, the radius calculated to be 1.492 RJ, showcasing a planet like Jupiter. The periodic of the light curve have a 3.69-day period. Detailed periodogram and phase-fold analysis are in the appendix. They follow suit with these observations, proving the idea of an exoplanet. The BLS periodogram as well shows a peak at 3.69 and the phase fold shows a dip in brightness.

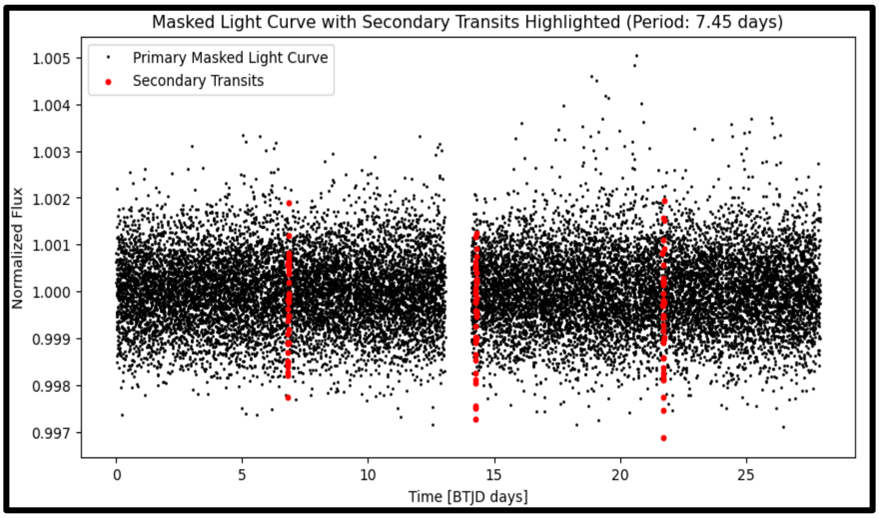


Fig.17: *Secondary Transits in Light Curve for Candidate 5: Dimming events marked in red every 7.45 days may indicate a planetary candidate to TIC 301072810.*

3.4.2 Tri-planetary System: Secondary Planet

TIC 301072810's second potential exoplanet: With a radius of 1.208 RJ, it is larger than Jupiter. The 7.45-day period. The Periodogram shows a peak at 7.45 and the phase fold shows a small dip in brightness.

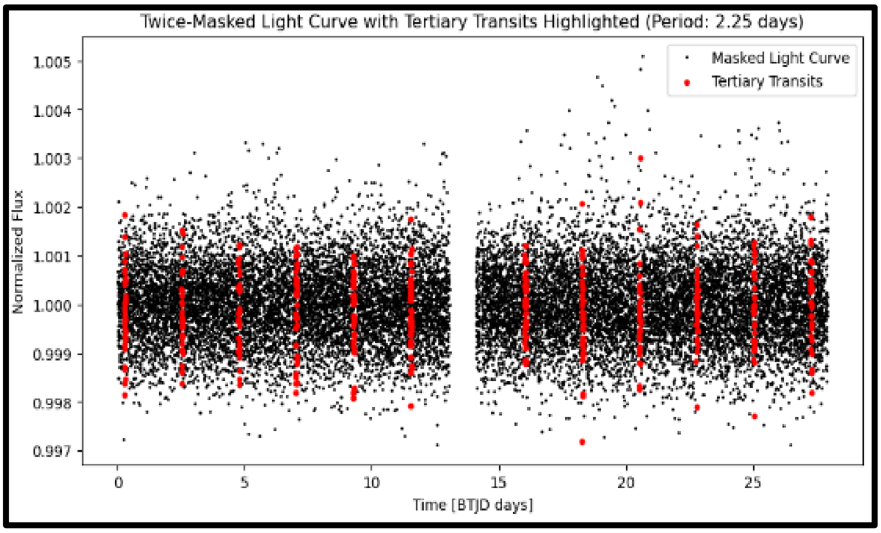


Fig.18: *Tertiary Transits in Light Curve for TIC 301072810: The frequent dips highlighted every 2.25 days show a smaller exoplanet.*

3.4.2 Tri-planetary System: Tertiary Planet

TIC 301072810's third potential exoplanet: With a radius of 0.157 RJ, appears to be a small-scale exoplanet with a very small 2.25-day orbit. The light curve reveals a periodic pattern of transits. The Periodogram shows the peak at 2.25 days and a tiny dip in brightness in the phase fold.

4. Discussion and Conclusion

The pursuit of exoplanetary discovery using the TESS data identified three compelling candidates, each presenting distinct characteristics. The detection methodology, based on the transit method and reinforced by highly technical computational tools, has shown the strength and reliability of the findings.

4.1 Interpretation of Findings

The light curve analyses for TIC 44792534, 460205581, and 207468071 points to exoplanetary bodies exhibiting transits with periodicities of 3.68, 8.32, and 20.38 days. The radius estimates 0.875, 1.21, and 0.73 Jupiter radii suggest a range of exoplanet sizes from a smaller gas giant to Jupiter-like sizes. The masking of primary transits and the careful approach in search of secondary and tertiary bodies show the depth of the analysis that was looked at during the project. This technique enhanced the detection capabilities and unveiled the intricate dynamics of potential multi-planetary systems.

4.2 Limitations and Constraints

While the analysis was comprehensive, it was littered with observational anomalies, such as for example TESS moving into the shadow of the earth, which impacted the data integrity. The reliance on computational models and the assumption of perfect heat redistribution are simplifications that won't show the full picture of what's really going on.

4.3 Further Research and Applications

Further observations and analyses, potentially through the James Webb Space Telescope (JWST), being able to perform spectroscopic analysis and radial velocity measurements, would provide a more compound understanding of these candidates that could reveal atmospheric compositions, verify the presence of moons or rings, and refine orbital characteristics/parameters.

4.4 Concluding Remarks

In conclusion, the identified candidates reflect TESS's capability to filter through cosmic noise and prove the value of transit photometry in exoplanet science. The collaboration of space-based telescopes (JWST) and ground-based observations will be huge help in reforming the findings and the stellar parameters found and help find planetary environments that are similar to our own, thereby getting closer to questions about life in the universe.

As we search through the universe, our project not only contributes to the growing catalogue of exoplanetary bodies but helps with the confirmation of these planets pushing for further study.

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https://www.youtube.com/watch?v=jbJTupzSfII - **Transit Method – Brian Gleim**

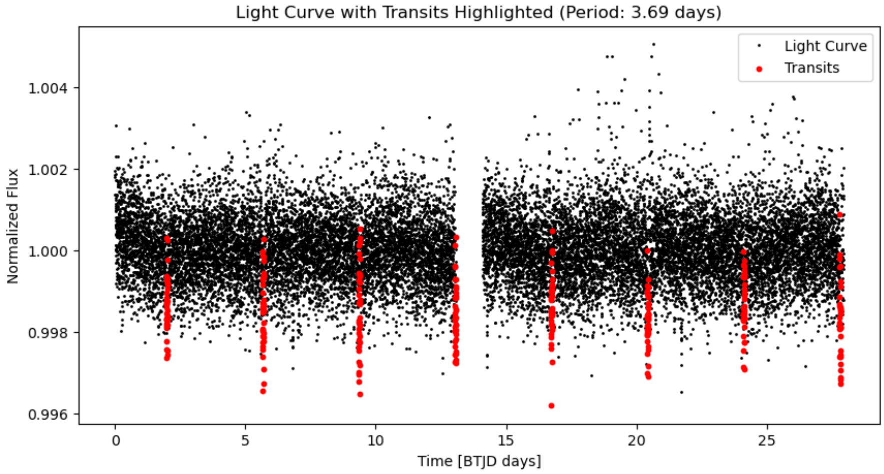
6. *Acknowledgments*

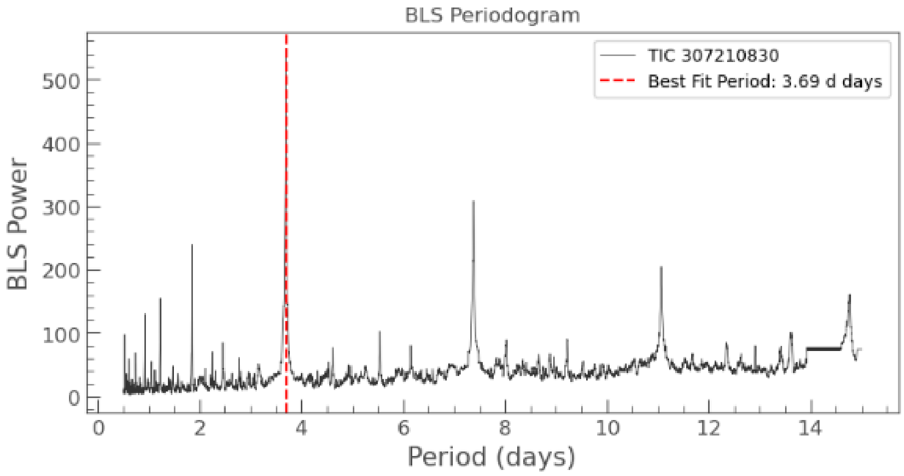
This report is based on a project carried out under the supervision of Senior Lecturer Meg Schwamb as part of the BSc degree in Queens University Belfast.

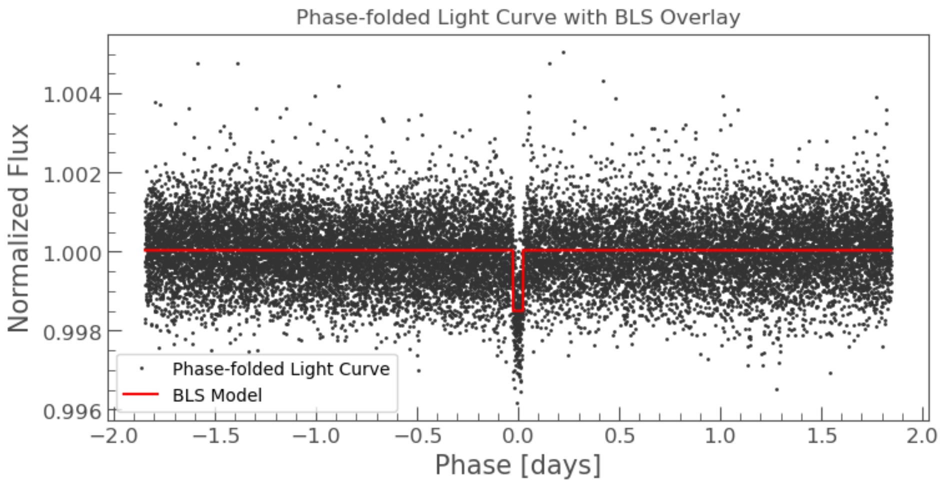
7. Appendix

3.4 Potential Tri-Planetary System (*TIC 307210830*)

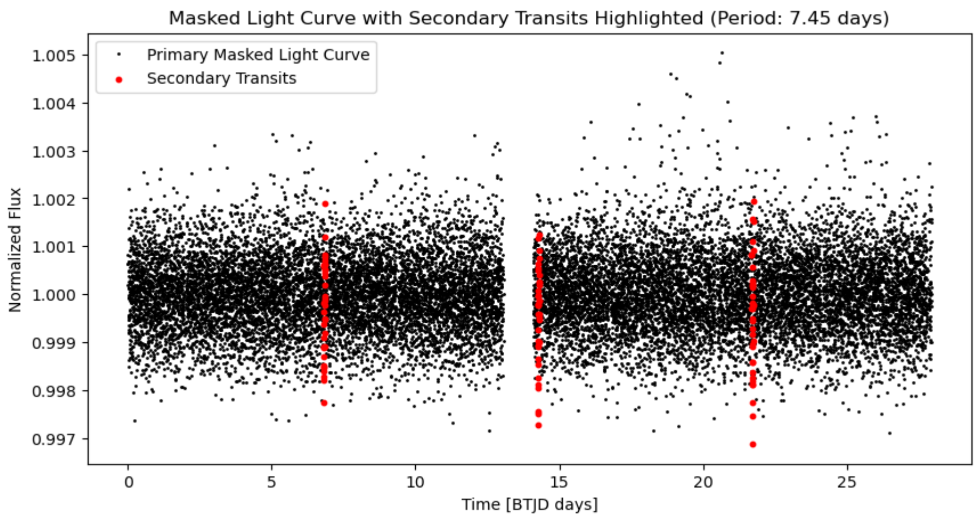
3.4.1 Tri-planetary System: Primary Planet

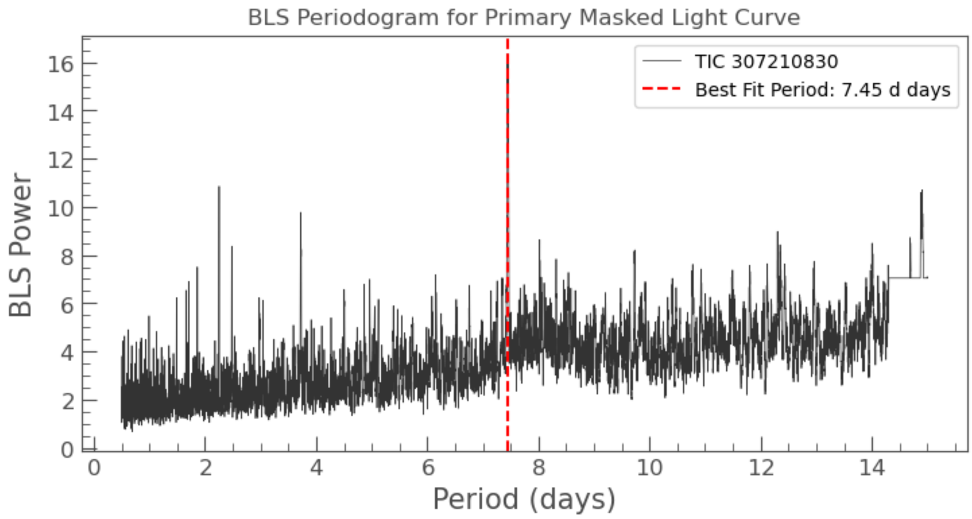


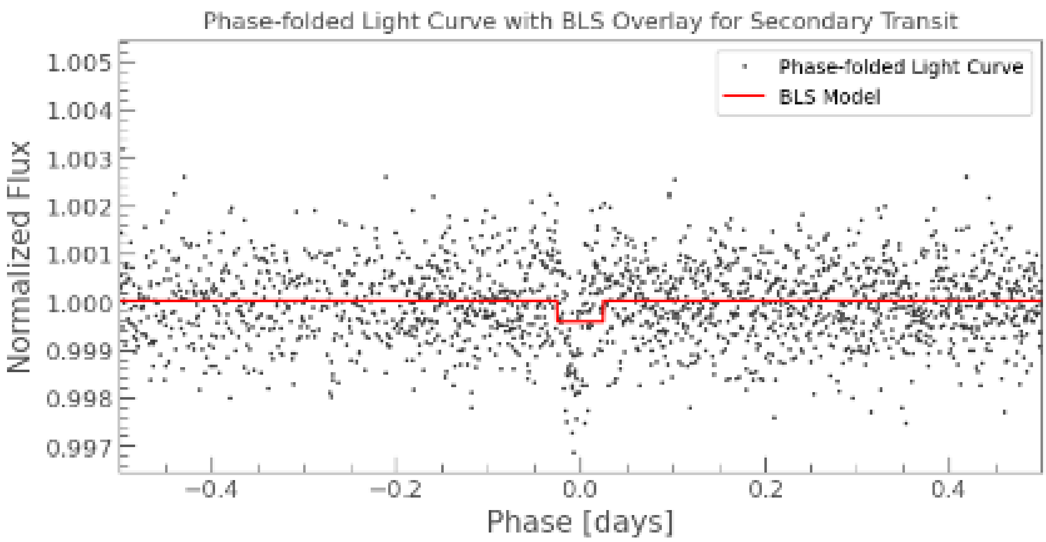




3.4.2 Tri-planetary System: Secondary Planet







3.4.2 Tri-planetary System: Tertiary Planet