Analysis of the Transit Method of Identifying and Classifying Exoplanets

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Abstract -

In this project, we investigate the (current) primary method to identifying and measuring exoplanets; The transit method is used to measure the drop in luminosity of distant stars as their respective exoplanets eclipse. By measuring the drop in luminosity during the ingress of the exoplanet, we can estimate the size of the planet. This allows us to document and classify exoplanets across the galaxy.

1. Introduction

The study of exoplanets is a fairly new subfield of astronomy, with the first exoplanet discovered in 1992 [1]. Since that first exoplanet was observed there have been 5,786 more planets discovered [2]. Locating, detecting, and measuring exoplanets is far from a perfect science with its relatively new establishment. In recent decades there have been a plethora of ideas of how to detect new exoplanets to study.

2. Existing Methods

There are numerous methods to identify exoplanets, the primary methods being pulsar detection, radial velocity, transit, gravitational microlensing, astrometry, and direct imaging [3].

Pulsar Detection- When massive stars near the end of their life cycle, there is a chance that the star collapses and experiences a supernova. The aftermath of this event may leave a remnant core called a neutron star. These stars are incredibly dense and may emit radiation in the form of radio waves. While orbiting the star emits these radio waves radially creating a pulsing effect. This pulsar star has a set and reliable period of emission. However there are slight disturbances due to the orbiting planets moving or otherwise affecting the neutron star. This can be measured to detect the presence of exoplanets.

Radial Velocity- Stars with particularly heavy plantes experience gravitational effects that manifest as a “wobble” of the star. The center of mass of the solar system will not be exactly centered to the star, this means that the star also follows an orbital path (though much smaller than the planets). This creates the "wobble" and can be quantified by the amount of red shifting (or doppler shifting [4]) the light emitted by the star experiences.

Transit- Some stars have a constant luminosity unless eclipsed by a dark body. In the case of studying exoplanets a planet will slightly dim the star while passing the star in reference to an observer. This slight decrease in luminosity can be measured to estimate the size of the orbiting body.

Gravitational Microlensing- This technique utilizes gravitational fields of a star and its exoplanet to shift the light such that the light is focused beyond the system [5]. The result of this focus can reveal the existence of an exoplanet along with information about the planet's mass and orbit.

Astrometry- By using stable reference stars, a star that has a relatively heavy exoplanet will appear to wobble. By using the subtle change in relative distance from the reference stars the mass of an exoplanet can be determined [6].

Direct Imaging- This method takes images of the planets by dimming the light of the star to try and observe the reflection of light off of the exoplanets [7].

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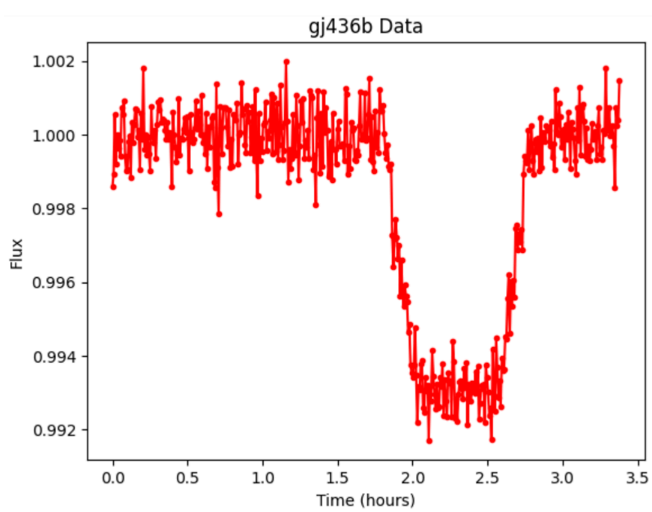
3. Process

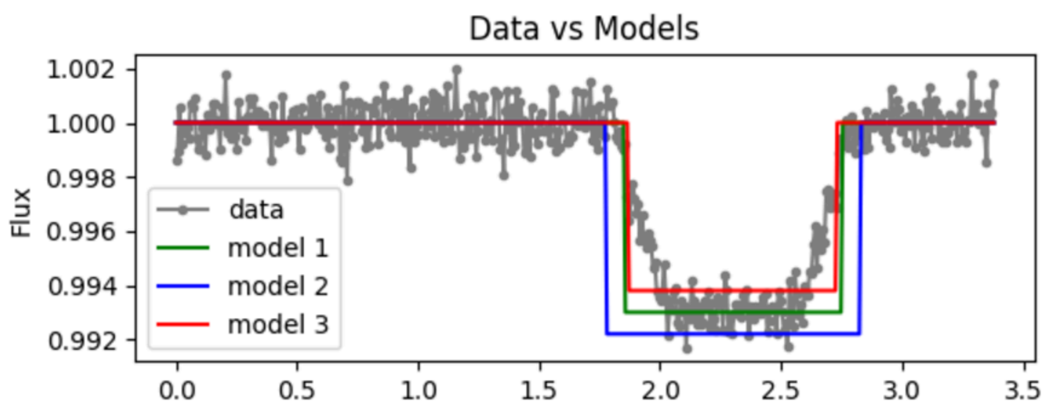
The process that has the most viability is the transit method. This method can be utilized primarily to identify and approximate the size of an exoplanet. This first required a set of data, this can be found at the NASA Exoplanet Archive [8]. The data of the transit period looks like this.



This data can then be modeled using the following simple parameters and equations given the central time of the event, duration of the event, change in luminosity and duration of observation.

```
# Creating the shape of a light curve
def generate_transit_lightcurve(time_arr, t0, tau, delta):
  flux_arr = np.zeros(np.shape(time_arr)) + 1.0
  time_start = t0 - tau / 2
  time_end = t0 + tau / 2
  ind = np.where((time_arr >= time_start) & (time_arr <= time_end))
  flux_arr[ind] = 1 - delta
  return flux_arr
```

This basic model can then be adjusted to fit the data to give a more basic understanding of the data. We initially started with 3 different models that we thought would under predict, over predict, and a model in between. This initially worked well to reduce the over representation of the data.



However we knew that we could do better than randomly guessing. To find a more precise way to find our model we created a simple iterative system to run through all local possibilities to return the best model for our data.

```
#Quick algorithm to run through all options to find the best fit
best_chi2 = np.inf  # Initialize with a very large value
best_params = {2.3,.764,.0064999999}  # Dictionary to store best
parameters

#Creating scanning ranges
t0_range = np.arange(2.25, 2.35, 0.01) * u.hour  # Range of t0 values
tau_range = np.arange(0.7, .95, 0.001) * u.hour  # Range of tau values
delta_range = np.arange(0.005, 0.008, 0.0005)  # Range of delta values

#Looping through all possibilities in the range of interest
for t0 in t0_range:
    for tau in tau_range:
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```
            for delta in delta_range:
                flux_model = generate_transit_lightcurve(time_obs, t0, tau,
delta)

                # Calculate chi-squared
                ind = np.where(time_obs < 1.5 * u.hour)
                error = np.std(flux_obs[ind])
                chi3 =  np.sum(((flux_obs - flux_model)/error)**2) /
Deg_Freedom

                # Update best parameters if chi-squared is less than current
best_chi2
                if chi2 < best_chi2:  # Comparing directly with chi2
                    best_chi2 = chi2
                    best_params = {'t0': t0, 'tau': tau, 'delta': delta}

    #Print results
    print("Best-fit parameters:", best_params)
    print("Best chi-squared:", best_chi2) # Print the best chi-squared
```

This enabled us to define local ranges of all of our parameters to systematically sort through all possible options. We started with a large scanning range using large step sizes to increase the efficiency along with decreasing the computation time. Once initial results were returned we saved the best values and ran the system again but decreasing step size and scanning area. This allowed us to fine tune our model to eventually get what we found to be the most accurate approximation.

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4. Results

Analysis of the model shows the drop in luminosity to be approximately .0065. Using the equation below we can estimate the radius of the exoplanet in reference to the star's radius.

$$\delta = \left(\frac{Rplanet}{Rsun}\right)^2 \rightarrow Rplanet = \sqrt{\delta} \times Rsun$$

We determined that the radius of the exoplanet observed is roughly 8.06% of the observed star.

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5. Discussion

The applications of the transit method are vast, while the difficulty of each step of the process remains relatively easy. Gathering data is often a struggle in the field of astronomy and can slow down scientific discovery. However with the transit method the only data required is to measure the luminosity drop of a star. This in comparison to other methods is far more practical. Along with that this method can also be repeated as the exoplanet orbits around the star. By only requiring basic algebra we can approximate the luminosity drop quite well, this results in a much more efficient process from start to finish.

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6. Conclusions

It should not be a surprise to see that the transit method is the leading method to identify and discover new exoplanets. The versatility and (relative) simplicity has allowed astronomers to identify 2,771 planets [9]. To collect the data required also only requires amateur level equipment, basic knowledge of astronomy, and basic arithmetic.

References

[1] - How the first exoplanets were discovered

[2] - Exoplanet - Wikipedia

[3] - What are Exoplanets & How Do We Find Them?

[4] - 17.8: The Doppler Effect - Physics LibreTexts

[5]- Microlensing - NASA Science

[6]- Wobbly Stars: The Astrometry Method | The Planetary Society

[7]- What is the Direct Imaging Method? - Universe Today

[8]- NASA Exoplanet Archive

[9]- What is the Transit Method? - Universe Today

AI Statement

Our group did have assistance with generative AI through Gemini AI, this was used in the coding aspect of the project to help look up how certain functions work along with help debugging and optimizing our basic iterative optimization model. AI was used to look up certain syntax issues and to explain bugs in the code when debugging.

Work Statement

Work was evenly distributed with both members working on all aspects of the project. To cater to each group members strengths each group member specialized as we saw fit, this distribution is as follows:

Everett was the lead in the written report with a majority of the written components and formatting. It was also his responsibility to proofread and correct the slides for the oral presentation.

Ember was the lead on the oral report slides and presentation preparations. In addition most code referenced is Ember's code for this project. It was also her responsibility to proofread and correct the written report.

Both group members helped each other on their respective part of the project to ensure the best product we could produce.