Detection of Exoplanets using Transit Method

Project Report

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1. Exoplanets

An Exoplanet is a planet, much like the ones in our own solar system, that we have discovered to be orbiting a star(or a star system) other than the Sun. The first ever exoplanets were found in the late 20th century (the first one fitting the modern definition of exoplanets was found in 1995) and since then, over thousands of exoplanets have been identified.

Though most exoplanets mirror the planets we know in our Solar System, others are very hard to recognize. As such they’re classified in various categories:

- Hot Jupiters: Gas giants orbiting extremely close to their host stars. They’re similar to Jupiter but have small orbital periods($P<10$ days).

- Super Earths: Also known as mini-Neptunes, these planets are gas-dwarfs with mass significantly higher than the Earth but smaller than Neptune or Uranus.

- Circumbinary Planets: Planets found to be orbiting a system of two closely orbiting stars.

2. How are Exoplanets Detected?

2.1 Radial Velocity (RV) Method:

The RV method is one of the most common and successful detection methods. It is based on detecting the wobble of the planet’s parent star as the planet orbits the star. The changes in the velocity of the star are detected by means of Doppler shifts in signatures that are imprinted on the light from the star.

2.2 Transit Photometry Method:

This method detects the planet, orbiting its host star, by detecting the minute dips in the brightness received from the star as the planet comes between the Earth and the star. The phenomenon of the passing of an object between Earth and the star is termed as “Transit”. If the transit is found to be periodic and lasting a constant length of time, then it is highly probable that a planet has been detected.

The dimming of the star provides a measure of the size of the planet: small planet implies smaller dip, large one implies large dip.

3. Exoplanetary Transit:

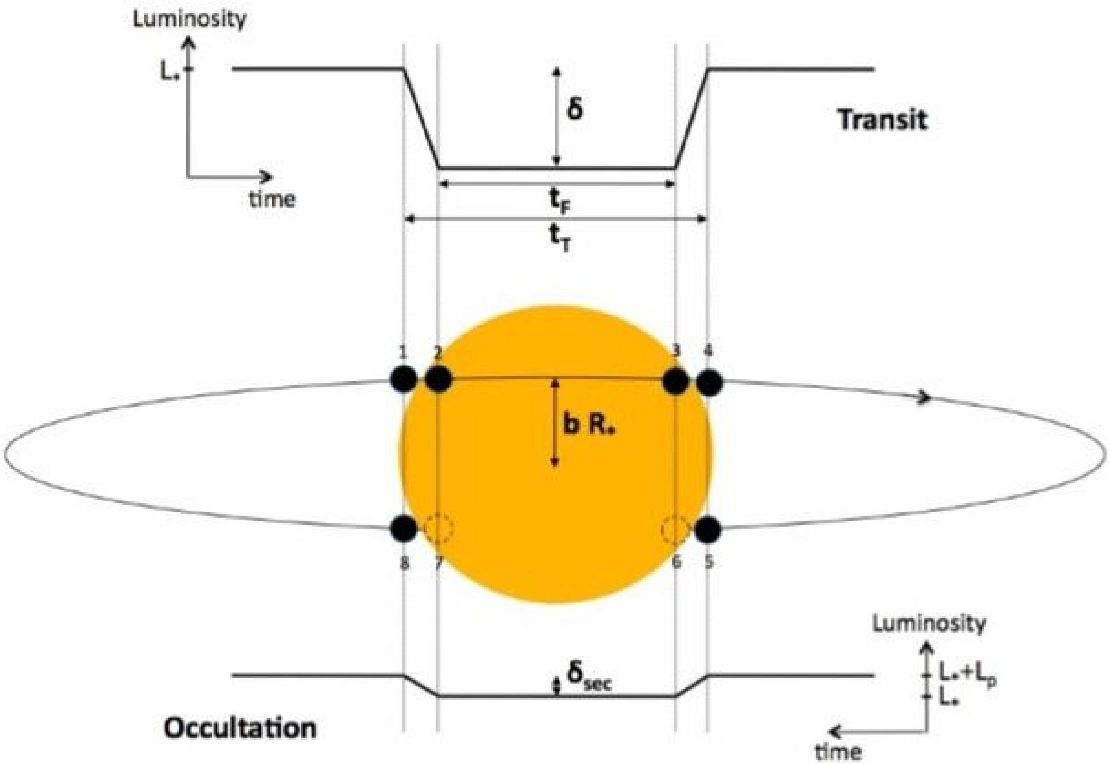

Fig: The schematic of a planet transiting its host star (middle) with the corresponding variation in brightness during the transit (top) and during the occultation (bottom). The impact parameters b and the transit parameters (δ, t_F, t_T) used in the equations are indicated on this figure.

An exoplanetary transit is satisfactorily visible only when the orientation of the orbital plane is sufficiently close to the "edge-on", i.e, inclination angle $i \approx 90°$.

When the angle i is not 90°, the transit is observed at a distance bR_s from the stellar diameter, R_s being the star's radius. Here, the parameter b is known as the **impact parameter.** It is given as

$$b = \frac{a \cos i}{Rs}$$

Where 'a' is the orbital radius.

Now, let the quantity δ be defined as the ratio of the dip in the brightness to the non-transit brightness of the star. Then, by Stephan-Boltzmann's law, it can be shown that

$$\delta = \left(\frac{Rp}{Rs}\right)^2$$

As such, the radius of the planet can be determined easily. It is to be noted here that the transit light curve is not perfectly flat-bottomed due to an effect known as limb darkening. This causes the expression for δ to change. However, for our purpose, we will ignore these effects.

After this point, we can further our calculations and make appropriate approximations to arrive at the following results:

$$b = \sqrt{\frac{(1-\sqrt{\delta})^2 - (t_F/t_T)^2](1+\sqrt{\delta})^2}{1-(t_F/t_T)^2}}$$

$$\frac{a}{R_\star} = \frac{2P}{\pi}\frac{\delta^{1/4}}{\sqrt{t_T^2 - t_F^2}}$$

Where t_F, t_T and P indicate the **full transit time**, the **total transit time** and the **orbital period** respectively.
Total Transit Time: The total time for which the planet is transiting.
Full Transit Time: The time for which the entire planet is blocking light from the star.

4. Current Implementation:

The implementation done by us is using the flux data of the Kepler 8 star. The data has been acquired by the archives of the now retired Kepler telescope (https://archive.stsci.edu/kepler/). The data requires some preprocessing, which includes:

- Filtering out flux from non-optimal pixels: The .fits data provided by Kepler contains the information about the pixels of the aperture that are to be used in calculating the total SAP_FLUX for a particular cadence. Thus, the flux data from the non-optimal pixels is to be filtered out
- Handling missing values: The data also contains some missing data points. Our implementation has deleted these points.
- Flattening of the lightcurve: The lightcurve had a typical low frequency downward trend, which was filtered out (using the Savitzky-Golay high pass filter).
- Normalisation: After flattening, the SAP_FLUX was normalised using min-max normalisation.

The transit of a planet is periodic. After performing the above steps, period of the transit is obtained using the Box Least Squares Algorithm. The period of transit is typically equal to the orbital period and thus allows us to determine the phase the planet is in at various cadences.

Folded LightCurve: After obtaining phases, we are now able to generate a folded light curve, i.e., a curve between normalised SAP_FLUX and phase. This curve is now used to determine δ (the dip ratio in flux), t_T and t_F.

Now that we have all the required quantities, we can calculate the various physical parameters associated with the planet.

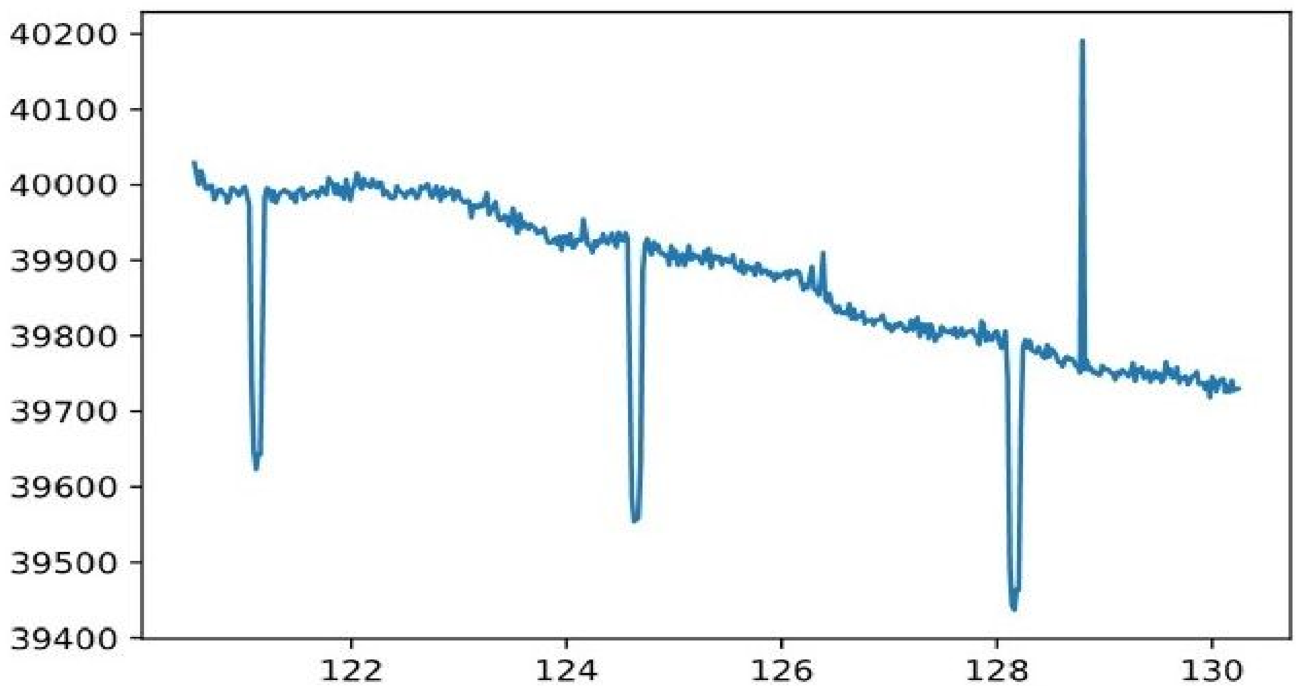

Fig: The initial unflattened lightcurve. Horizontal axis denotes the BKJ date of the cadence, while the vertical axis denotes SAP_FLUX

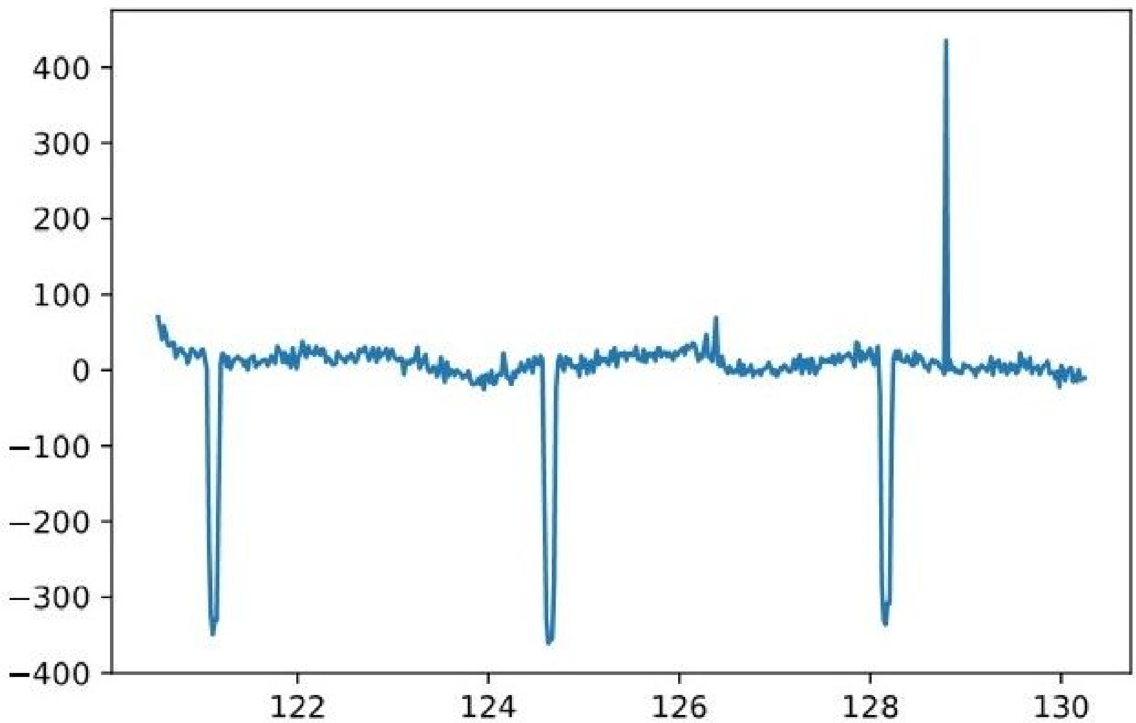

Fig: Flattened LightCurve

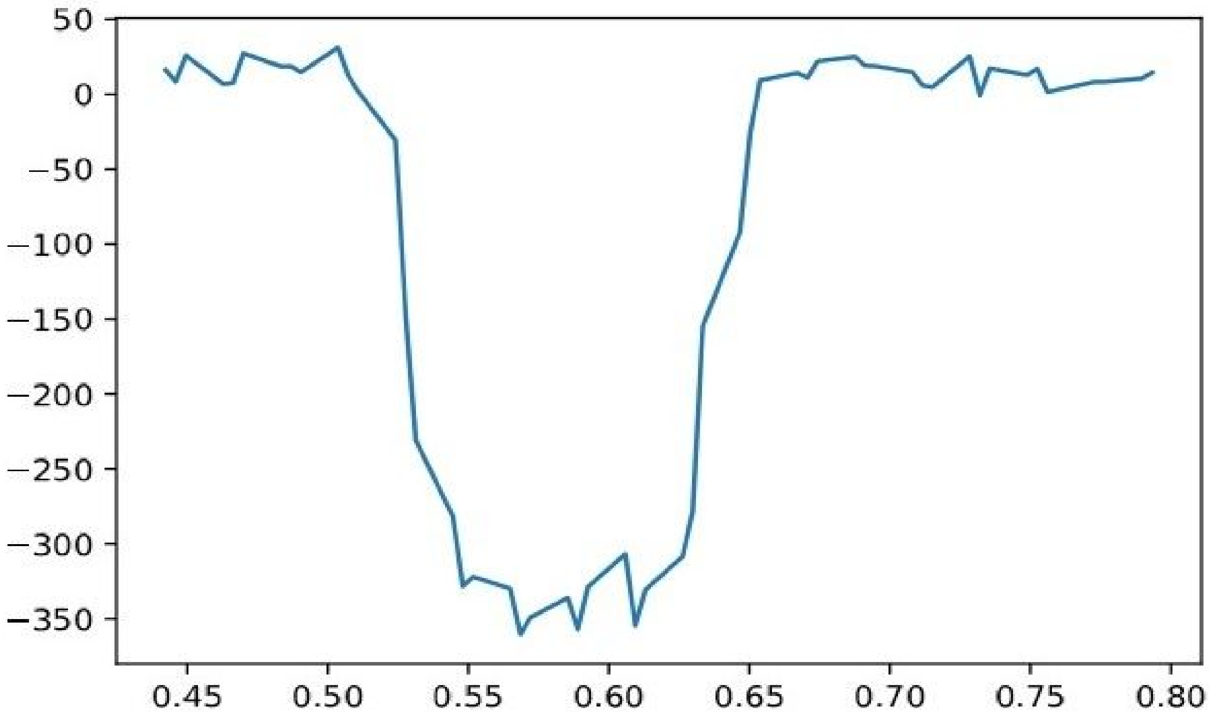

Fig: The Transit

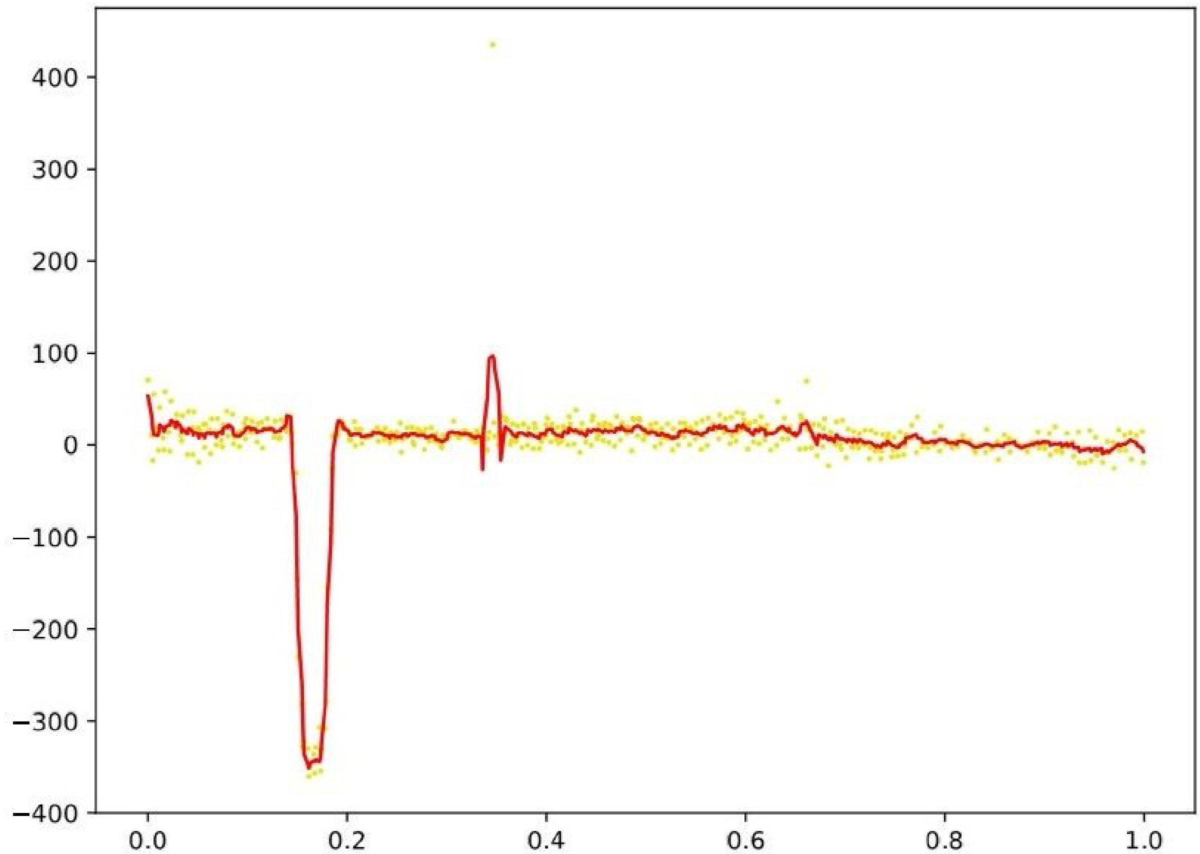

Fig: Folded LightCurve. The yellow scatter points are the actual data points while the red curve is the best fit model for the SAP_FLUX.

The findings of are:

Maximum depth in flux, δ_{max} = 0.00888

Total Transit Time, t_T = 0.1502 days

Full Transit Time, t_F = 0.0985 days

Orbital Period, P = 3.5183 days

Radius of the host star (given as a part of the data) = 1.486 AU

5. Results:

The analysis of the Kepler 8 lightcurve strongly indicates the presence of an orbiting planet. This is indeed the planet Kepler 8b, which is characterised by the following parameters:

1. Orbital period of the planet is about 3.51 days or 84.25 hours.
2. Semi Major axis of the orbit is 0.0409 AU.
3. Radius of the planet is 1.386 times that of Jupiter. It is a very large planet.
4. The orbital inclination of the planet's orbit is found to be about 83.07°.

These values are compared with the values available on Wikipedia.
Orbital period has an error of 0.88%, radius has an error of 2.3%, inclination has an error of 1.18% and semi major axis has an error of 14%.