Exoplanet Detection via the Transit Method

Irtaza Tanveer Ahmad[1] **and Muhammad Sabieh Anwar**[1]

[1]PhysLab, School of Science and Engineering, Lahore University of Management Sciences.
[*]24100039@lums.edu.pk and sabieh@lums.edu.pk

ABSTRACT

The transit method is amongst the most widely employed techniques utilized to detect and characterize exoplanets orbiting distant stars. By exploiting the subtle dimming of a host star's brightness as an exoplanet passes in front of it, astronomers can obtain information about the exoplanet such as its size and orbital characteristics. The aim of this computational laboratory is to acquaint students with the basics of the transit method by making use of data from the Kepler Telescope to re-detect exoplanets that have already been discovered.

This work has been funded by the National Centre for GIS and Space Applications, Pakistan.

Version March 14, 2024

Motivation: Why search for exoplanets?

One of the fundamental principles of the scientific method is the idea of putting theories and models to test by gathering observational data, seeing if the current theories we have are able to explain what we actually see to some reasonable degree and if not, try to work towards models which can explain observations in a better way. We saw this principle in action as quantum physics explained atomic phenomena better than the Bohr model of the atom. One of the leading theories of planet formation right now is the nebular theory. Although it is able to explain various aspects of how various planetary systems such as the Solar System come about, it is not a perfect theory and needs to be improved upon. For this we need to obtain more data from various other planetary systems in our universe, and use that data in order to refine the nebular theory. This is why searching for exoplanets becomes incredibly important. Not only does it allow us to expand our map of the universe but the insights we can fetch from exoplanetary systems improve existing theories of how planets form and evolve.

Introduction to the Transit Method

Now that we have motivated a need to discover exoplanets, the next question is "How do we look for them?" Although there are a number of methods, the most popular one in observing exoplanets today is the **transit method**. Not only is it highly popular, it is highly successful as shown in Figure 1 [1]. According to this figure, around 78% of all the exoplanets discovered in 2018 had been discovered using the transit method.

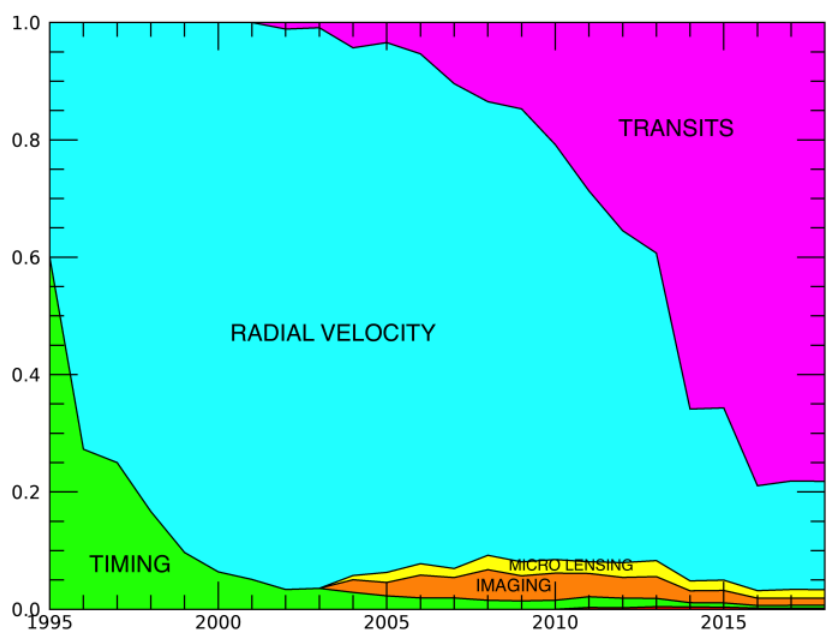

Figure 1. This figure shows the fractions by which various exoplanet detection methods contributed to the pool of known exoplanets from the years 1995 to 2018.

How does the Transit Method work?

The transit method makes use of the fact that if an exoplanet revolves around a star, then some of the light which is emitted by the star is blocked out by the planet. This is similar to what we see during a solar eclipse, when the moon comes between the earth and the sun and blocks some of the sun's light for a short period of time. More formally, if we measure the flux (which is related to the brightness) of a star against time, then when the exoplanet passes through the star (this is usually referred to as the **transit event**), we would observe a dip in brightness which would then return to its normal value when the planet has passed through the star completely [2]. The plot of the star's flux against the time is called the **lightcurve** of the star and is commonly used by astronomers to detect and characterise exoplanets. All of this is pictorially shown in Figure 2 below.

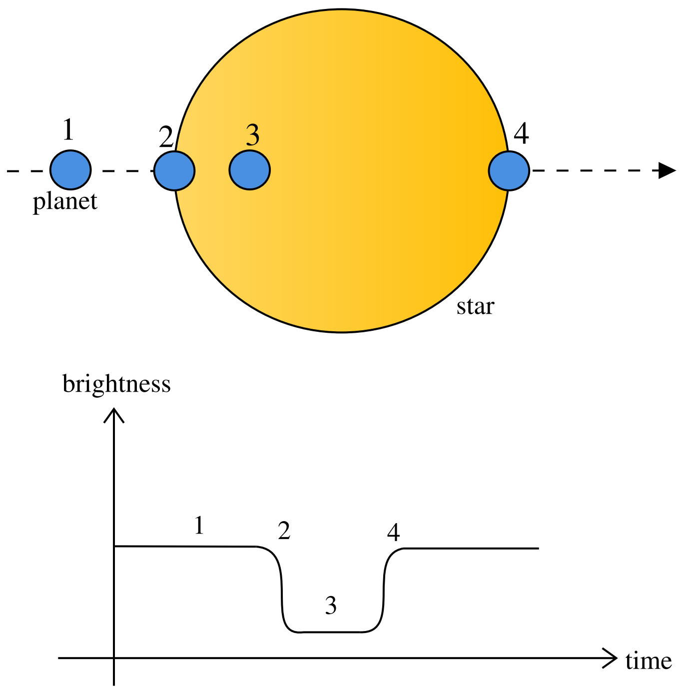

Figure 2. A diagram showing the transit event of a star and the associated lightcurve.

An excellent indicator of whether there is an exoplanet revolving around a star is when the dips in the lightcurve as shown in Figure 2 occur periodically. This necessitates the need to continuously look at various stars outside the solar system for long periods of time in order to establish any periodicity and improve results; if we only look at a star during the perceived transit event, it might lead to a false positive.

What information can we obtain from the Lightcurve?

Let us assume that we have found evidence of an exoplanet orbiting some star and have the corresponding lightcurve of the star at hand as well. The first piece of information one can obtain almost immediately is the orbital period of the planet, which will be denoted by P. This would correspond to the time difference between two transit events in the lightcurve. Another quantity which can be determined is the semi-major axis a of the exoplanet. This is given by

$$a = \left(GM_s \left(\frac{P}{2\pi} \right)^2 \right)^{\frac{1}{3}} \tag{1}$$

where M_s is the mass of the star and G is the universal gravitational constant.

Q1 Derive Equation 1. (*Hint:* Recall Kepler's Laws.)

A third quantity which can be determined is the radius of the planet R_p assuming that the radius of the star R_s is known. This is given by

$$R_p = R_s\sqrt{\Delta F} \tag{2}$$

where ΔF is the transit depth, which refers to how much flux has been blocked out compared to the unblocked condition [1]. Equation 2 simply comes from the fact that flux is proportional to area and radius is proportional to square root of the area.

Detecting the Exoplanet Kepler-8b

Exoplanet detection using the transit method has become a lot easier nowadays due to a number of computational libraries which have been developed by astronomers and researchers. One such library is the Python library *lightkurve* [4]. This library allows for individuals familiar with basic Python programming to readily grasp the basics of common techniques used by astronomers to detect exoplanet transits. The reader is also encouraged to explore the documentation of the *lightkurve* library which can be found here. As an introduction to using this library to detect a known exoplanet, a Google Colab Notebook can be found here which goes through the detection of Kepler-8b alongside determining its orbital period and transit depth.

The Google Colab Notebook for Kepler-8b is by no means an comprehensive introduction to how the transit method is used by researchers for exoplanet detection. An attempt has been made to explain some of the basics of this method such as obtaining a periodogram to analyse periodic trends in the lightcurve, designing specific masks to remove anomalous data from the analysis, the usage of aperture masks to obtain a lightcurve which is easier to analyse and folding a lightcurve for better analysis. However, the reader is encouraged to consult the *lightkurve* documentation as well as the following YouTube playlist [3] to understand these techniques in more detail. In particular, these resources contain material related to the technique of **binning** the lightcurve to reduce the amount of noise in the data which could lead to inaccurate results and predictions. Since this laboratory mainly involves detecting known exoplanets, the Colab Notebook also includes a basic overview of how to navigate the NASA Exoplanet Archive [5] in order to ascertain whether the results obtained for various stellar parameters match the results obtained by various researchers.

Q2 Determine the semi-major axis of Kepler 8-b. How can you check the validity of your calculation using the NASA Exoplanet Archive?
Q3 Determine the radius of Kepler 8-b using the value of the transit depth determined in the Colab Notebook. Cross-check your value against the values provided in the NASA Exoplanet Archive.

Q4 Detecting the Exoplanet Kepler-10b

Now that you have been acquainted with the basics of exoplanet detection by means of the transit method, your task is to detect the exoplanet Kepler-10b, the first terrestrial planet[1] discovered by the Kepler Telescope. Furthermore, determine the orbital period, semi-major axis and the radius of the exoplanet. Before you proceed, you are highly encouraged to read up on analysing noise in lightcurves by consulting the YouTube playlist previously mentioned as well as the *lightkurve* documentation.

[1] A terrestrial planet is a planet that is composed primarily of silicate rocks or metals in contrast to planets such as Jupiter which is mainly comprised of various gases.

References

[1] Hans J. Deeg and Roi Alonso. “Transit Photometry as an Exoplanet Discovery Method”. In: *Handbook of Exoplanets*. Springer International Publishing, 2018, pp. 633–657. DOI: 10.1007/978-3-319-55333-7_117. URL: http://dx.doi.org/10.1007/978-3-319-55333-7_117.

[2] Brian Gleim. *Transit Method*. 2020. URL: https://www.youtube.com/watch?v=jbJTupzSfII.

[3] Planet Hunters. *All our episodes in order*. URL: https://www.youtube.com/playlist?list=PLpTcgCRPTgRk3uXOM6Ee5A1Y1F61zOXBz.

[4] Lightkurve Collaboration et al. *Lightkurve: Kepler and TESS time series analysis in Python*. Astrophysics Source Code Library. Dec. 2018. ascl: 1812.013.

[5] California Institute of Technology. *NASA Exoplanet Archive*. URL: https://exoplanetarchive.ipac.caltech.edu/.