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Effect of neighbouring planets on detecting Extra-solar Earths

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ABSTRACT

Life is most likely to evolve on planets with conditions similar to those on Earth (Earth-like). There are a number of upcoming space missions that aim to find such planets in our galaxy. 'Earth 2.0' is one such mission. The mission uses the transit method to detect planets, where we look for a slight dimming of the star's light when a planet crosses its face. This is a very small signal and is easily lost due to stellar noise and other complications. My project studies one such complication: the effect of a neighbouring planet. A neighbouring planet can disturb the orbit of the transiting planet, making it less regular and causing slight transit timing variations (TTVs) every orbital period. This TTV will make the planet more difficult to detect. It is therefore important to find the magnitude of TTV caused by neighbouring planets. To study this, I ran 50,000 computer simulations of planetary systems, with the neighbouring planet's orbital elements varying within set ranges. I then recorded the TTV of the Earth-like planet in each system. This data was then used to find the amount of signal degradation due to the neighbouring planet. Overall, the results show that while some cases were influenced by the neighbouring planet and exhibited a significantly higher TTV, the majority of transit signals were still detectable. Neighbouring planets do not significantly affect the TTV, and therefore the chance of detection, of Earth-like planets.

KEYWORDS

Astrophysics, Exoplanet detection, Earth-like planets, Transit timing variation

INTRODUCTION

Context

The search for other life in our universe has intrigued humanity for thousands of years. Yet to this date, no such life has been discovered. While this life may take many forms, recognizable life is most likely harboured and found on exoplanets with conditions similar to those on Earth. Therefore, the ideal planet meets three criteria: it is terrestrial and of a similar size to Earth, orbits a star similar to the Sun, and has an orbital distance comparable to Earth's (i.e. 1 AU). This ideal planet will be referred to as an 'Earth-like' planet throughout the paper.

To this date, no such planets have been found.

This is not from a lack of trying. The Kepler mission is one of the most significant recent missions. It was launched in 2012 and ran for four years, ending in 2016. Using the transit method of detecting exoplanets (explained below), the mission detected more than 4000 planets. However, it failed to detect any Earth-like planets due to its short duration and limited data [1].

Yet the search for another planet like ours continues. The space mission 'Earth 2.0' (preliminarily titled) was recently approved and funded by the Chinese National Space Center to start phase-A study. The goal of the mission is to find Earth-like planets in our galaxy [2]. It is planning to launch in 2026 (11 years after the end of Kepler) and run until 2030. Over these four years, seven small telescopes will continuously observe the light variations of roughly one million stars. The mission will watch the same patch of sky as the Kepler mission. Together, humanity will have stared at these stars for a total of eight years. During this time, an Earth-like planet will have transited eight times, significantly increasing our ability to detect it.

Kepler's failure to find any Earth-like planets can be attributed to the difficulty of detecting such planets, as discussed below. There is a narrow margin of error, which leaves the success of the Earth2.0 mission (and future missions working towards the same goal) vulnerable to possible complications, which must be examined. One such complication is the effect of a neighbouring planet, which is investigated in this original work.

Detecting exoplanets

Finding planets is not as simple as staring through a telescope to see them physically. Planets themselves do not emit light and only partially reflect their host star's light. They can be more than a billion times fainter than the star and are extremely difficult to detect visually using ground- or space-based traditional telescopes [3]. As such, they must be found using indirect methods.

The most successful approach to detecting exoplanets is the transit method [4]. As an exoplanet transits across its host star, it results in a slight dimming of the light from that star received by our telescopes (a 'dip' in light level; see Figure 1). Once detected, this dip provides important information about the planet [5].

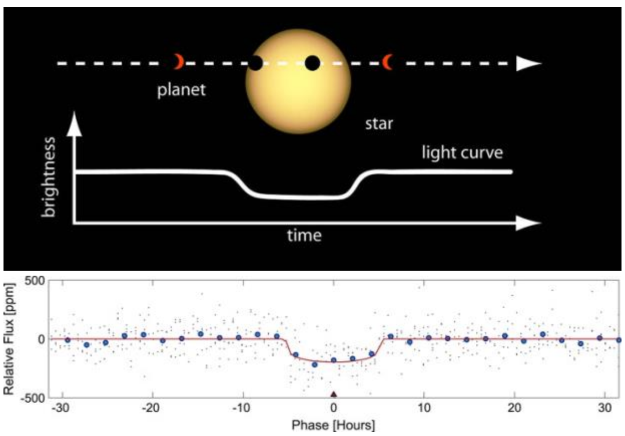


Figure 1. Transit of an Earth-like planet in front of its host star from NASA [6] (top) & Jenkins et al. [7] (bottom). The small blue dots (bottom) are the light levels of the host star, observed over a period of four years, and folded together by the planet's orbital period. The star light is fluctuating and makes a single dim transit hard to recognize. By 'folding' the data, repeated transits stand out.

The failure of the Kepler mission to detect any Earth-like planets is due to the inherent difficulty in detecting such planets. Earth is incredibly small in proportion to the Sun. Its transit results in only a 0.0084% decrease of the Sun's light level [5]. Earth-like planets can be assumed to have similarly small transit dips. Transits are also rare. Earth has an orbital period of a year and its full transit lasts only 13 hours. The outcome of these two factors is a very shallow and short transit dip, making the signal difficult to detect. Further narrowing the margin of error are large natural fluctuations in stellar light known as 'noise', which obscure the transit signal.

Trying to find this single, tiny transit signal amongst all the surrounding stellar noise is impossible. It is analogous to trying to hear someone whispering across a room full of shouting people. The current approach is to record the light level of the host star over a long period of time. This data can then be 'folded', revealing repeated dips in light level at regular intervals caused by the transit of the Earth-like planet each orbital period (Figure 1). Evidently, the longer we watch the sky, the more transit dips we will detect, and the easier it will be to find planets by folding.

The transit method of detecting exoplanets relies on the repetition of the transit dip at strictly periodic intervals. This leaves the technique vulnerable to complications that can affect the transit timing of the planet each orbital period.

Neighbouring planets

One such complication is the effect of a neighbouring planet. Analysis of Kepler data brought to light that a majority of exoplanet systems contain multiple planets [8]. It has also shown that within these systems the planets are spaced closely, with significant planet-planet interactions [8]. These results suggest that many Earth-like planets will have neighbouring planets close enough to have a gravitational effect on them, thereby influencing the Earth-like planet's transit. This transit timing variation (TTV) decreases our ability to detect the transit dip (see Figure 2). It is therefore important to find the magnitude to which neighbouring planets affect the transit timing of Earth-like planets, and consequently our ability to detect them.

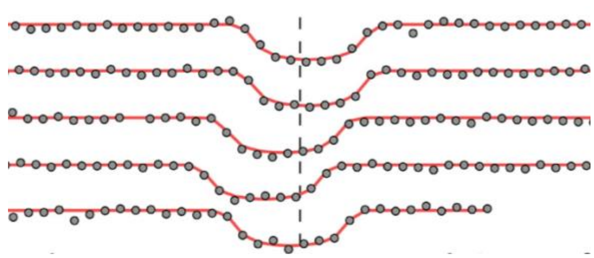


Figure 2. Variation in transit timing due to the non-transiting neighbouring planet of KOI-872b from Nesvorny et al. [9]. The significant variations in each transit timing due to the gravitational perturbations of a neighbouring planet are evident here. This makes it more difficult to 'fold' the data as there is no distinct orbital period. Additionally, the slight timing variations will result in a shallower and broader dip if the data is folded.

This hinders our ability to detect the transit dip, and therefore detect the transiting planet which caused it.

Present study

I make the assumption here that the studied Earth-like planet resides in a planetary system similar to our own solar system, with neighbouring planets comparable to Jupiter, Mars, Venus, etc. In this project I first assess which neighbouring planet has the greatest effect on our ability to detect Earth-like planets. I then investigate the magnitude of that effect as well as its implications on detectability (ΔSNR, discussed in 'Methods').

METHODS

Resources

In this work, all numerical simulations and analysis are run using Python. I also use the packages 'Rebound' [10], 'NumPy', and 'Matplotlib'. Rebound simulates a planetary system by using Newton's laws to calculate the position and velocity of each of the bodies involved over the length of the simulation.

Venus-like planets

We assume the exoplanetary systems of the studied Earth-like planets are similar to our solar system. Given this assumption, the neighbouring planet that has the greatest effect on Earth's transit timing each period is our sister planet, Venus. A reasonable expectation might be that Jupiter, being the largest planet within our solar system, will have the greatest effect on Earth's TTV. However, several preliminary simulations (procedure detailed in 'Recording transit timing variation') prove that Venus causes the most variation due to its closer orbit. The average TTV of Earth due to the effects of Venus (0.05 hours/orbital period) is 10 times larger than that caused by Jupiter (0.005 hours/orbital period). Therefore, this study focuses on the effect of planets similar to Venus ('Venus-like' planets) on the detection of Earth-like planets in exoplanetary systems.

Exploring parameters

While we assume these exoplanetary systems to be similar to our solar system, we naturally do not expect them to be identical. Therefore, some orbital elements (see Figure 3 for 'orbital elements') of the three bodies involved in this project (the host star, the Earth-like planet, and the Venus-like planet) are set to vary within certain ranges.

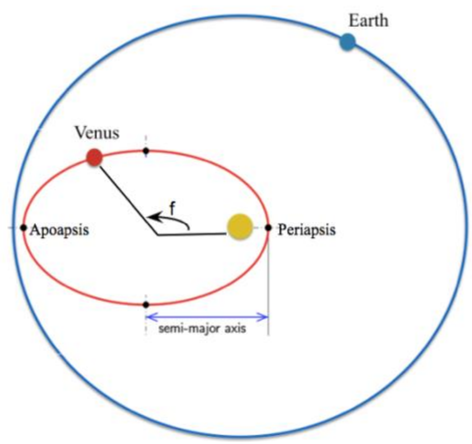


Figure 3. Orbital elements. Semi-major axis (also called the orbital distance) is the distance from the center of the ellipse to the furthest point. Eccentricity is the deviation of the ellipse from a circle. True anomaly (f) is an angle defining the position of the body along its orbit (between periapsis and the current position of the body). Argument of periapsis (ω) defines where the orbiting body will reach periapsis. Eccentricity and argument of periapsis are not depicted.

I assume the host star is of the same size as our Sun and that the Earth-like planet is at a distance of 1 AU from the star and has an eccentricity similar to Earth's, as specified by the term 'Earth-like' planet. We are mainly interested in exploring the neighbouring Venus-like planet's parameters, in order to determine the magnitude of its effect in a range of orbits. I set four of the planet's orbital elements to vary within ranges defined below. Each unique combination is termed a 'case' going forward.

Mass	2.45×10^{-6} *
Semi-major axis ('a')	0.7 – 0.85 AU **
Eccentricity ('e')	0.0 – 0.2
True anomaly ('f')	0 - 2π
Argument of periapsis ('ω')	0 - 2π

*compared to the mass of the star, which is set to 1

** the orbit is assumed to be inside that of Earth

Within this range it is also critical to remove any unstable systems. Unstable systems are planetary systems in which the orbits of member planets cross or closely approach each other, which may cause them to collide or eject each other. Unstable systems do not exist in nature, and as such should not be included in the data.

First, any cases where the orbits of the Venus-like planet and the Earth-like planet initially cross are removed. This is done by finding the minimum semi-major axis of the Venus-like planet that will result in a crossing (a_{crit}). However, many unstable cases still exist where the orbits do not initially cross but will closely approach each other after a while. I simulate a sample set of systems using Rebound, for 10,000 years each, with a minimum exit distance set to 0.05 AU. This allows me to determine an approximate boundary between stable and unstable cases, which is found to be $0.93a_{crit}$. All cases past this boundary are removed from the dataset.

Finally, after the TTVs are calculated for each case (next section), all cases that remain with a TTV > 9 hours are retested, and all are shown to be stable without exception. There are 49,434 stable cases out of 50,000 total cases.

Recording transit timing variation

For each stable case, a simulation of a planetary system with a star, an Earth-like planet, and a Venus-like planet is set up. The latter's orbital element values vary within the ranges defined above. Each system is simulated for 19 years using the 'TransitTimingVariation' subroutine of Rebound. This subroutine records the exact times at which the Earth-like planet transits the star from the perspective of an observer (the satellite).

While we know that the orbital period of Earth is precisely 1 year and can use the information recorded above to calculate TTV based on that expected period, other Earth-like planets may have periods that vary slightly. Thus, a linear regression is applied to the simulation data and the variation from that apparent period is recorded for each transit. This TTV is due to the gravitational perturbations of the Venus-like planet.

These 19 years of TTVs account for 4 years of data from the Kepler mission, 11 years of no data between missions, and 4 years of data from the 'Earth 2.0' mission. Only data for the first and last 4 years of the data is stored, accounting for the missing 11 years of data.

Calculating impact on detection

After recording TTV, the next step is to find its impact on our ability to detect the Earth-like planet.

A signal's 'signal to noise ratio' (SNR) is a quantitative measure of how detectable it is. In this case, SNR refers to the strength of the transit dip caused by Earth's transit across the sun (i.e. the 'signal'), compared to the amount of random stellar fluctuations (the 'noise'). A higher SNR is ideal, as it implies that the signal is stronger and more easily detectable.

For each case, I create two 8-year models of light-levels for the star of the Earth-like planet. The first model represents a system in which the transit of the Earth-like planet is strictly periodic (a system 'without-Venus'). The second accounts for TTV (a system 'with-Venus). Both these light-level models contain 140160 'bins', each representing a half hour of the star's light level. For reference, the transit of the Earth-like planet only alters the light level in 26 of these bins (13 hours) per orbital period, or only 0.15%. I add random noise appropriate for a Sun-sized star (normal distribution [11], mean=0 and FWHM=5 x 10^{-5}) equally to both models. I fold both 8-year models into one year, shallowing out the transit dip of the Earth-like planet in the case of the 'with-Venus' model. This also reduces the effect of noise.

Next, I run a simplified version of a box-least square computer code to find the transit dip [12]. This cycles through 1600 variations of transit depth and duration and compares them to the models in order to determine what the computer 'thinks' is the transit dip. It is used to find the SNR for both systems using the following formula:

$$SNR = \sqrt{\Sigma(\frac{signal}{noise})^2}$$

*'Signal' is expressed as a percentage of the star's light level decrease caused by the transiting planet.

**'Noise' is the FWHM of the random stellar noise added. FWHM describes the percent by which the star's light level fluctuates.

After calculating the SNR for the two systems, I take the difference (ΔSNR) in order to find the effect of the Venus-like planet on our ability to detect the Earth-like planet.

$$\Delta SNR = SNR_{\text{without Venus}} - SNR_{\text{with Venus}}$$

A lower ΔSNR is ideal, as it implies that the Venus-like planet has minimal effect on our detection of the Earth-like planet. I obtain one ΔSNR value for each case.

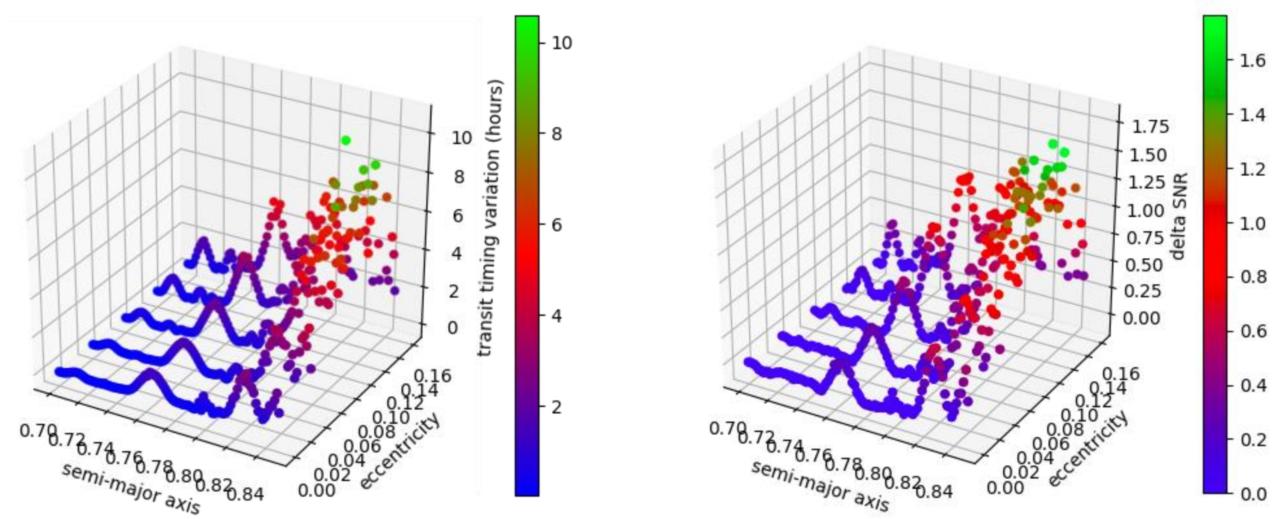
RESULTS

Here, I present the results using MatPlotLib. The relationship between the Venus-like planet's semi-major axis and eccentricity, and the Earth-like planet's TTV are shown below (Figure 3a). The same information is also conveyed with a different unit, ΔSNR, for better visualization of our ability to detect the Earth-like planet. (Figure 3b)

Noticeably, the average TTV of the Earth-like planet is correlated with the semi-major axis and eccentricity of the Venus-like planet. As its semi-major axis and eccentricity values increase, so does its effect on the Earth-like planet (i.e. TTV), up to a maximum of around 9 hours of variation. This is expected. Higher semi-major axis and eccentricity values will bring the Venus-like planet's orbit closer to the Earth-like planet's, allowing it to exert a greater gravitational pull on the Earth-like planet. This stronger gravitational perturbation results in further deviation of the Earth-like planet from its periodic transit times and larger TTVs.

For reference, our solar system's Venus has a semi-major axis of 0.72 and eccentricity of 0.01. It causes an average TTV of 0.05 hours/orbital period on Earth. As such, it is represented by a point located in the bottom left corner of Figure 3. The 566 unstable systems removed were all of high semi-major axis and eccentricity values. All had TTV of over 9 hours. They would have appeared in the upper right quadrant of Figure 3a.

The disruptions at semi-major axis values ~0.70, ~0.76, ~0.82 seen in both figures are caused by orbital resonance, which usually occurs when the orbital periods of two bodies can be expressed as a ratio of small integers. This results in their orbits approaching each other at periodic intervals, thereby allowing them to exert a regular gravitational pull on each other. In these cases, the Earth-like planet's orbit is further disturbed and there is greater TTV.



<u>Figure 3a (left). Effect of Venus-like planet's semi-major axis and eccentricity on an Earth-like planet's transit timing variation (TTV).</u> Each point represents the average of 100 simulations with varying true anomaly and argument of periapsis values at given semi-major axis and eccentricity values. TTV for each simulation is averaged over 8 years. As semi-major axis and eccentricity values get higher and the Venus-like planet's orbit approaches that of the Earth-like planet, TTV can become as high as ~10 hours. This is significant variation when considering the Earth-like planet's 13-hour transit. Certain locations show bumps due to 'orbital resonance'.

<u>Figure 3b (right). The vertical axis now represents change in signal to noise ratio ΔSNR.</u> If ΔSNR > 1, planet transit detection is significantly more difficult.

The detection threshold of missions using the transit method is around SNR = 7 [13] [14]. As the SNR of a transit dip decreases, the chances of it being a false positive increase. Any signal lower than around SNR = 6 gives little confidence in the detection of an exoplanet [12]. Since the transit signal of any Earth-like planet will likely be bordering the detection threshold, a reduction in SNR greater than 1 (ΔSNR > 1) due to the neighbouring planet is harmful.

Using this as a boundary for detectability, only 11.07% of all cases are 'undetectable'. For reference, ΔSNR = 1 corresponds to an average TTV of around 4 hours, from numerical experiments. Of course, this boundary is slightly arbitrary. Yet even in an extreme scenario where it is lowered to ΔSNR = 0.5, we still find that only around 20% of cases are 'undetectable'.

Of note, all 'undetectable' cases have high semi-major axis and eccentricity values, which can result in an unstable system. These cases should be further investigated to see whether they can exist in nature (i.e. are stable over a long period of time). Should a significant portion be found to be unstable, the effect of neighbouring planets might be even more minimal than my results show.

Overall, Venus-like planets do not significantly affect the detection of Earth-like planets in around 90% of cases I investigated.

DISCUSSION

My results show that neighbouring planets will not greatly affect our ability to detect Earth-like planets when using the transit method in the large majority of cases.

Limitations

These results are based on a series of assumptions:

- The planetary systems of the Earth-like planets resemble our own solar system (ex. a Jupiter-sized planet orbiting at a Venus-like distance would be problematic)
- Several orbital elements of the Earth-like planet and Venus-like planet
- The 'satellite' captured every transit possible (for instance, Kepler did not make observations during a fraction of its mission time [15])
- A simplified calculation of SNR
- The detection threshold is similar to Kepler's, i.e. SNR = 7 (expanded on below)

All of these assumptions must be examined further in order to more accurately quantify the impact of neighbouring planets on our detection of Earth-like planets.

Implications and future research

My results resolve one of the potential complications hindering detection of Earth-like planets, namely the effect of a neighbouring planet on our detection.

This is good news and it allows us to turn our focus to other potential complications. These must also be explored before we can successfully find Earth-like planets. Complications might either obscure the transit or create a false positive of a transit signal.

Finally, stellar noise is currently the foremost problem in the detection of Earth-like planets. The transit dip is easily lost in stellar noise caused by the flickering of the star. This necessitates the long-term recording of star light-levels in order to view multiple transits and the 'folding' of the data to find these transits. One hope is that we will develop artificial intelligence (AI) able to remove most of the stellar noise using machine learning algorithms [16]. This would lower the detection threshold and be a crucial step towards finding new planets, and possibly other life in our universe.

CONCLUSION

Discovering Earth-like planets is an ambitious endeavour and faces many complications.

We believe that many of these planets may have one or multiple neighbouring planets, just as our Earth does.

Gravitational perturbations from these neighbouring planets may affect our ability to detect Earth-like planets by causing variations in their transit timing.

Earth transits our Sun once every year, and the transit lasts ~13 hours. This is assumed to be true for all Earth-like planets. A shift in transit time of greater than 4 hours means the Earth-like planet's transit will most likely be undetectable.

Venus's perturbations of Earth cause an average TTV of 0.05 hours/year. Other planets in our solar system, including Jupiter, result in even smaller TTVs. When we explored Venus-like planets in a range of similar orbits, the TTVs they generated were less than 4 in the large majority of cases (88.93%), which does not significantly hinder our ability to detect them

The small minority (11.07%) of cases considered undetectable should be investigated further to see if these systems can exist in nature. In these cases, the Venus-like planet's orbit closely approaches the Earth-like planet's orbit, which can result in an unstable system.

Overall, our results show that nearby Venus-like planets do not significantly affect the transit timing, and therefore our ability to detect Earth-like planets. This is good news.

Now that the effect of neighbouring planets on Earth-like planet detection has been shown to be minimal, we can turn our focus to other complications hindering our detection of these planets. One hope is that advances in AI could aid our search for Earth-like planets, and extraterrestrial life.

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