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Simple and general methods to identify terrestrial planets

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Abstract. This paper has introduced and examined some methods to generally distinguish whether an exoplanet is terrestrial, with the help of available data. These methods include analysing the exoplanet's orbital period, size, distance from the star, and density. By comparing these properties with the known characteristics of terrestrial planets, we can make an informed judgment about whether an exoplanet is terrestrial or not. Using the transit method, we can find an exoplanet and determine its orbital period and size. By applying Kepler's Third Law together with the radial velocity method, we can calculate the star-planet distance and the planet's density, respectively. However, it is important to note that these methods have their limitations and uncertainties. The transit method is limited by the probability of observing a transit due to randomly oriented planet systems, and the radial velocity method is only highly receptive to detecting massive planets in close proximity to the stars they orbit. Additionally, certain astrophysical phenomena can lead to false positives in exoplanet detection. Despite these limitations, the methods presented in this paper provide a foundation for determining the likelihood of an exoplanet being terrestrial. As technology advances and our understanding of exoplanets expands, we will continue to refine these methods and develop new ones, improving our ability to explore terrestrial planets and potentially discover life beyond our solar system.

Keywords: terrestrial planets, exoplanets, space exploration, earth-like planets, transit method, radial velocity method.

1. Introduction

The exploration of terrestrial planets, which are rocky planets analogous to Earth, has been a key focus of space exploration for many decades. With the aim of a more complete understanding of the universe, and the goal to seek for another "home" to humankind, many missions have been initiated. The first successful mission to explore a terrestrial planet was Mariner 2 projected by NASA, which flew beside Venus in 1962 and provided the first close-up look at the planet [1]. Since then, several other missions have been launched to explore Venus, as well as Mars and Mercury, the other two rocky planets in our solar system. Since then, remaining terrestrial planets have been explored by several other missions.

Mars has been the most extensively explored planet of the terrestrial planets, with numerous missions from multiple space agencies sending spacecraft to study the planet. Some of the most notable missions include NASA's Viking 1 and 2, which landed on Mars in 1976 and recorded the image of Mars surface [2]. Following Viking 1 and 2, the Mars rovers Spirit and Opportunity landed in 2004 and explored the planet for several years with exciting findings that Mars once possessed habitable environment for microbes [3]. More recently, NASA's Curiosity rover has been exploring Mars since 2012, and the agency's Perseverance rover landed on Mars in February 2021.

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Mercury, the smallest of the terrestrial planets, has been explored by only two spacecraft so far. One of them is NASA's Messenger, which orbited the planet from 2011 to 2015. The mission provided data including Mercury surface temperature and detailed images of the planet's surface [4, 5]. These findings helped scientists better understand its geology and composition.

Venus, the closest planet to Earth, has also been the subject of several missions, including NASA's Pioneer Venus, which orbited the planet in the 1970s. Following that was the European Space Agency's Venus Express. This spacecraft orbited Venus from 2006 to 2014. Most recently, NASA announced two new missions to explore Venus: VERITAS, which will map the planet's surface in high resolution, and DAVINCI+, which will send a probe to study the atmosphere of Venus.

Investigating rocky planets has offered crucial understanding regarding the formation and development of our solar system, in addition to the potential of life existing outside of Earth. With new missions planned in the coming years, including the Mars Sample Return mission and the Europa Clipper mission targeting Europa, Jupiter's icy moon, the exploration of terrestrial planets will continue to be a key focus of space exploration in the years to come.

Beyond the exploration of rocky planets in proximity in the solar system, various methods have been introduced accompanied by other spacecrafts to discover terrestrial exoplanets. As of 2023, 5272 planets have been confirmed, with 195 of them being terrestrial [6].

This paper intends to introduce and examine some methods to generally distinguish whether an exoplanet is terrestrial, with the help of available data.

2. Prerequisite: find an exoplanet

The principle is to find an exoplanet and examine if it fits the properties of a terrestrial planet, including orbital period, size, distance from the star, and density. An exoplanet must be identified as existing first before comparing its properties with the terrestrial planet's properties.

This can be achieved using a transit method [7]. This method detects exoplanets by observing regular decreases in a star's luminosity when a planet transits (moves in front of) the star's disk. (Figure 1). In this figure, the black circle represents the star, and the white circle represents the planet. The three figures demonstrate the change of relative position between the planet and the star with time. The following steps demonstrates the method:

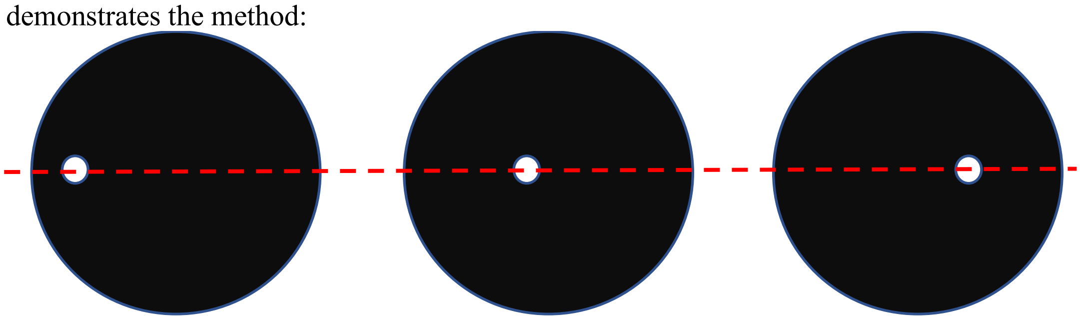

Figure 1. Visualization of transits.

Step 1: Observing a Star: The first step in the transit method is to observe a star for an extended period of time. This allows to detect any periodic changes in its brightness caused by the presence of exoplanets. The brightness is measured with high precision for accurate analysis. This is usually done using a photometer, which can detect changes in brightness in high precision. One of the commonly observed databases used for analysis is obtained from Kepler's missions [8]. Kepler's data is what will be used for later demonstration.

Step 2: Detecting a Transit: When an exoplanet transits its star, it blocks a minor portion of the star's light, resulting in a reduction of brightness. The depth and duration of the dip depend on the size of the planet and the period of its orbit.

Step 3: Confirming an Exoplanet: To confirm that a transit is caused by an exoplanet, multiple transits must be observed with their depth and duration measured to be the same.

As an example, the following graph (Figure 2) is plotted with corrected star flux against time in BJD.

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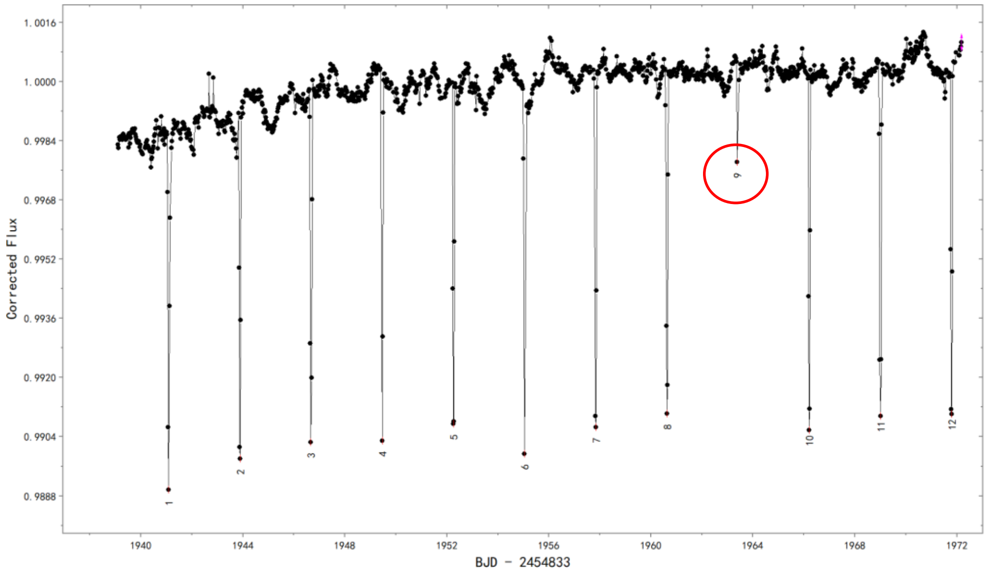

Figure 2. Flux of star EPIC 202126852.

It is seen that except for the 9th transit circled in red, other transits have constant frequency of occurrence and similar depth and duration. It can be therefore concluded that a planet orbits the star EPIC 202126852.

It is notable that despite the simplicity in transit method detection, certain defects come with the method. Firstly, the probability of transits being observed from the earth is low, due to the randomly oriented planet systems (Figure 2) This is because the earth, the exoplanet and its sun are not aligned. Hence, the number of terrestrial planets to be discovered in transit method will be much fewer than the real amount. Another shortcoming is that there exist certain astrophysical phenomena which lead to similar observations as transits, resulting in false detection positives [9].

With the confirmation of the existence of an exoplanet, further determination of its properties can be proceeded to be compared with the criteria of terrestrial planets.

3. Criteria

3.1. Criterium 1: orbital period

The orbital period can also be determined using the transit method. This is done using the number of transits and total time recorded. In the following example, EPIC 202126852 is again referred to.

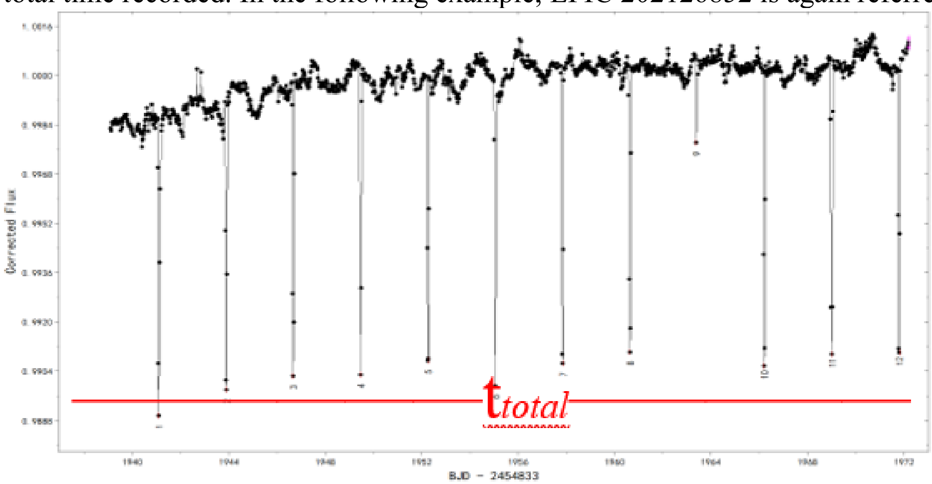

Figure 3. Total time of recorded transits of EPIC 202126852.

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The following calculation includes the anomalous 9th transit as it has constant frequency with other transits.

Total number of transits is,

$$N_{transit} = 12 \tag{1}$$

Total time during these transits is as shown in Figure 3,

$$t_{total} = 737\,h \tag{2}$$

Hence, the period is given by,

$$Period = \frac{t_{total}}{N_{transit}-1} \quad 3)$$

In this specific case, period of transit is 2.792 days.

Nevertheless, it is difficult to conclude on the identity of an exoplanet with merely its orbital period. This is especially so for a terrestrial planet, as terrestrial planets exhibit orbital periods ranging from less than one day to 4300 days [10, 11]. In this case, even though the exoplanet has its orbital period in the range of terrestrial planets, it is still unclear whether it is terrestrial. Therefore, it is necessary to introduce other criteria to refine the identification.

3.2. Criterium 2: size

The size of an exoplanet can also be obtained using the transit method. This is done using the transit depth and the published data of the star orbited by the exoplanet. The following example will refer again to EPIC 202126852.

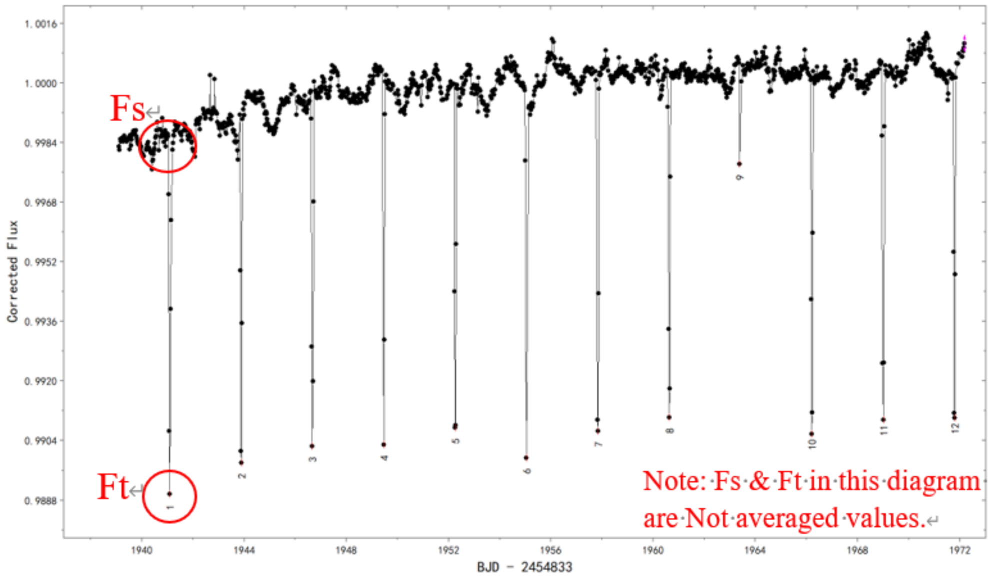

Figure 4. Transit depth of EPIC 202126852.

There are a few values to be pre-calculated as shown in Figure 4:

Averaged star flux Fs: Average of all corrected flux.

Averaged transit flux Ft: Average of all corrected flux at the lowest point during transits.

With these, the transit depth of the planet can be calculated:

$$depth = \sqrt{\frac{F_s - F_t}{F_s}} \tag{4}$$

Hence, the radius of the exoplanet is given by:

$$R_p = R_s \times depth = R_s \times \sqrt{\frac{F_s - F_t}{F_s}} \tag{5}$$

In this specific case, radius of the exoplanet is calculated to be 98184km.

Terrestrial planets are generally smaller than gas giants like Jupiter and Saturn. By definition of earth-like planets, they usually have radius of 0.5–1.4 $R_{\oplus}$ [12]. Therefore, EPIC 202126852 is unlikely to be a terrestrial planet as its radius is much larger than the criterium.

It is notable that in the calculation, the data of the 9th transit excluded. This anomalous point due to unknown reasons may bring in errors in the estimation of Ft. In addition, the representation of normal star flux by averaging all the corrected flux is questionable with respect to its accuracy as the transit flux ought not to be included in the estimation of normal star flux. Nevertheless, other attempts of more precise data manipulation have been tested by the author. They do not significantly reduce percentage error when compared with the published data. These attempted methods will thus not be brought up.

3.3. Criterium 3: distance from the star

The star-planet distance can also be determined using the transit method with proper manipulation of the K2 data. With orbital period of the exoplanet calculated in section Criterium 1, the distance between the exoplanet and the star can be simply estimated using Kepler's Third Law. The following demonstrations continue to use EPIC 202126852.

From section Criterium 1 we have,

$$Period = \frac{t_{total}}{N_{transit}-1} = 2.792 \text{ days} \tag{6}$$

Then we can apply Kepler's Third Law,

$$T^2 = \frac{4\pi^2}{G(M_{star}+M_{planet})}a^3 \tag{7}$$

In this formula, T represents the exoplanet's orbital period and a represents the orbit's semi-major axis. T is in unit of second, s, and a is in unit of metre, m. Since the star's mass is typically significantly greater than the planet's, the planet's mass can be omitted in the calculation, which would not significantly affect the accuracy of estimation. Therefore, we have:

$$T^2 = \frac{4\pi^2}{GM_{star}}a^3 \tag{8}$$

And therefore:

$$a = (T^2\frac{GM_{star}}{4\pi^2})^{\frac{1}{3}} \tag{9}$$

In this specific case, given period of 2.792 days and star mass of 1.42 times mass of the sun, a is estimated to be 6.53×10^6 km [13].

Briefly speaking, terrestrial planets are usually found closer to their star than gas giants, in the "habitable zone [14]." This zone features temperatures that are optimal for the presence of liquid water on the planet's surface. Nevertheless, this range varies widely from star to star due to differing contributing factors including mass of the star [14], age of star [15] and specific formation and evolution process in the planetary system [16]. Therefore, it is difficult to give a general range of distance from the star to indicate the characteristics of a terrestrial planet. However, we can still examine this specific case, given that the host star is F-type. Kasting, Whitmire and Reynolds determined that F-type stars usually have a habitable zone of 1.4 to 2.4 AU [14]. The planet-star distance calculated above is around 0.0436 AU, which is much smaller than the range. Hence, it may be concluded that this exoplanet is unlikely to be terrestrial.

3.4. Criterium 4: density

The density of an exoplanet can be determined by combining transit method and radial velocity method, with the latter also referred to as Doppler method. The radial velocity method yields the mass of the exoplanet by measuring the minor fluctuations in a star's movement resulted from the gravitational influence of an orbiting planet. By observing how the star's spectrum shifts over time, the planet's mass can be calculated. This can be done through following steps:

Step 1: Measure the Doppler Shift: Observe the host star's spectrum over time using a high-resolution spectrograph. As the star approaches and recedes from Earth, the spectral lines shift towards shorter (blueshift) and longer (redshift) wavelengths due to the Doppler effect. The change in wavelength ($\Delta\lambda$) can be measured by comparing the star's spectrum to a stable reference spectrum.

Step 2: Calculate Radial Velocity: Convert the measured Doppler shift ($\Delta\lambda$) into a change in radial

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velocity (Δv) using the following formula:

$$\Delta v = c \times \left(\frac{\Delta\lambda}{\lambda_0}\right) \tag{10}$$

In this formula, c stands for light speed and λ_0 represents rest wavelength of the spectral line.

Step 3: Determine Orbital Parameters: Plot the radial velocity measurements over time and fit a sinusoidal curve to the data. The amplitude of the curve (K) corresponds to the maximum radial velocity change, and the period (P) corresponds to the planet's orbital period. This step can be done with the help of orbital parameters obtained in Criterium 1 so as to assure accuracy.

Step 4: Given the mass of the host star (Ms), Minimum Mass (m sin i) of the Exoplanet can be calculated. Use the following formula to compute the minimum mass (m sin i) of the exoplanet:

$$m \sin i = \frac{P \times K^3}{(2\pi \times G)^{\frac{1}{3}}} \times (M_S)^{\frac{2}{3}} \times \left(1 - e^2\right)^{\frac{1}{2}} \tag{11}$$

In this formula, m stands for planet's mass; i stands for the orbital inclination; G is the gravitational constant, and e represents orbital eccentricity.

Note that this method provides the minimum mass and not exact mass as the measured motion is a projection of the true motion on the sky plane. The exact mass can be obtained if the orbital inclination is measured or provided.

The radial velocity method is only highly receptive to detecting massive planets in close proximity to the stars they orbit, and its sensitivity decreases for smaller planets or those with longer orbital periods [17].

This method has been used by Huang et al. to analyze the mass of HAT-P-56b which is used as example earlier. The following is a sample set of radial velocities calculated (Table 1) [18].

Table 1. Relative radial velocities, and bisector span measurements of HAT-P-56.

BJD (2,456,900+)	RV (ms^{-1})	σRV (ms^{-1})	BS (ms^{-1})	σBS (ms^{-1})	Phase	Instrument
32.99501	68	114	48.70	82.40	0.937	TRES
34.00383	−376	152	150.10	57.10	0.299	TRES
34.99731	0	54	64.40	58.30	0.655	TRES
36.00811	−310	107	2.40	45.50	0.017	TRES
42.99104	−170	70	67.10	50.00	0.519	TRES
43.98771	−268	146	−161.50	56.80	0.876	TRES
44.97264	−558	119	−57.30	70.80	0.229	TRES
46.00112	−113	102	−63.80	74.60	0.598	TRES
58.97630	−493	99	−65.60	44.80	0.247	TRES
60.02365	−221	92	−32.30	65.70	0.622	TRES
60.97679	−150	114	49.20	67.20	0.964	TRES
61.96910	−544	78	−111.70	111.00	0.319	TRES
65.96895	−80	87	−43.50	52.20	0.753	TRES
69.93743	−649	95	−2.40	69.50	0.174	TRES
70.89553	−419	153	16.40	58.90	0.518	TRES
71.85396	−187	105	85.90	80.70	0.861	TRES
72.94426	−609	54	36.40	34.10	0.252	TRES
77.04183	−331	96	−52.80	47.40	0.720	TRES

From there, Huang et al. managed to compute the mass of HAT-P-56b as 2.18 times mass of Jupiter. This exoplanet hence has mass of 4.14×10^{27} kg. With this, the density of the exoplanet can be easily computed.

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$$\rho = \frac{Mass}{Volume} = \frac{Mass}{\frac{4}{3}\pi r^3} \tag{12}$$

With respect to HAT-P-56b, its density is calculated to be 1.04g/cm^3. This density is small and similar to that of Jupiter. This indicates that this exoplanet is likely to be comprised primarily of gases including hydrogen and helium and unlikely to have a solid surface [19]. Thus, it may be concluded that this exoplanet is unlikely to be terrestrial.

3.5. Overall result

To sum up, there are a total of three criteria, namely size, distance from star and density which gave negative result of terrestrial identity. Therefore, the exoplanet orbiting EPIC 202126852 is highly unlikely to be terrestrial.

4. Conclusion

The exploration of terrestrial planets has been a crucial aspect of space exploration. Various methods can be employed to identify their properties and determine if exoplanets possess characteristics analogous to terrestrial planets within our solar system. This paper discussed the transit method and radial velocity method, which are widely used in detecting exoplanets and determining their properties.

To distinguish a terrestrial exoplanet, several criteria were introduced and discussed, including orbital period, size, distance from the star, and density. This paper has also used EPIC 202126852 as an example and yielded the result that it is unlikely to be terrestrial. On top of the methods, there are limitations and uncertainties associated with each method, and these need to be considered when interpreting the results. Furthermore, the composition of exoplanet is not discussed in this paper, even though it is also an essential and deciding property of a planet. The model used in this paper is very much simplified and only provides a general identification. Uncertainties and anomalies should be considered when conducting research on a specific exoplanet.

The ongoing development of new technologies, such as advanced telescopes and instruments, will undoubtedly improve the sensitivity and accuracy of exoplanet detection and characterization. As our comprehension of planetary formation and development continues to advance, the search for terrestrial planets and the possibility of extraterrestrial life will remain a key focus in the field of astronomy and space exploration.

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