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Use the Transit and Radial Velocity Methods to Detect Exoplanet LHS 1140 b

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Abstract. With the trend of technology advancement and environmental resource depletion, scientists make a hard effort to explore exoplanets that have ideal conditions for new colonization. Although the telescope becomes innovative, it is capable of detecting longer expansion of space. However, farther planets need to use some methods, typically, the transit method and the radial velocity method. By using the radial velocity method, this research applies the data of radial velocity and the mass of the star to calculate the mass of the planet using a formula. Thus, the topic of this essay is to use both methods to show how they can detect exoplanets' mass and the location of revolving orbits. After that, the difference between the two methods needs to be determined because of the differences. Also, the implications of the radial velocity method are significant. Specifically, by using the data including the mass of the host star LSH 1140, the orbiting period of LHS 1140 b, also the radial velocity of LHS 1140 b, to deduce the mass of this exoplanet.

Keywords: radial velocity, exoplanet, transit, Doppler's effect, spectrum

1. Introduction

In the scope of observation on the universe throughout history, scientists are always seeking to detect planets with plausible habitability. The main reason is that Humanity has an extensive history of unsustainable resource consumption leading to ecological overshoot. The aggregate human demands on resources, driven by per capita consumption and population growth, have exceeded the planet's regenerative capacity since the 1970s. As a consequence, a consistent mission for scientists is to find a habitable planet like Earth. However, the essential question is how to detect an exoplanet since the telescope's vision cannot extend very far. Scientists can't usually visualize the planet; however, scientists found two precise and useful methods that can be adapted to most of the planets no matter it is a binary star system or a single star system. According to the previous research, the Gaia mission has full astrometric data for 1.5 billion stars, but only 34 million have radial velocity measurements [1]. Demonstrate that there is a strong bias when applying the radial velocity method to all kinds of planets, the relationship of which will determine the reason and provide the specific deviation. When it comes to the transit method, which can be classified with varied tools, including X-ray transit and also Photometric monitoring techniques [2, 3]. However, the precision is a subject that needs further improvement; one of the reasons might be its reliance on imprecise telescopes. In

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short conclusion, both methods of transit and radial velocity have strong potential to generate unreal solutions, largely due to extremely long distances, attraction force, and other factors.

This essay is an example of using the transit method and radial velocity method, using the method on a certain planet, to find its mass and density, also showing the process of how scientists use these methods to detect an exoplanet, and also using the previous research data to suggest possible strengths, weaknesses, and biases of each method. The final purpose is to find the habitability of the planet by using the two methods as an implication of the two methods.

2. Method

2.1. General information

In this essay, LHS 1140 b plays the role of the investigating target. This research will use the transit method as well as the radial velocity method to deduce the process of detecting this exoplanet. To start with, LHS 1140 b is a super-earth exoplanet in the habitable zone, which orbits an M-type star. Its mass is 6.38 Earths, it takes 24.7 days to complete one orbit of its star, and it is 0.0957 AU from its star. Its discovery was announced in 2017 [4]. Both methods can be applied to LHS 1140 b because this exoplanet's detection is based on transit photometry. For a short explanation, the Transit method is basically utilizing the photometer to detect the brightness of a star, because when a planet moves across the surface of the star, there is a phase where it is dimming for a period of the planet's movement. Though there may be an inclination angle from the version of Earth, a precise photometer can capture the dimming period at a glance. For LHS 1140 b, the relevant data is shown in Table 1.

Table 1. Basic data obtained for LHS 1140 b [4]

Property	Amount	Unit
Orbital period	24.737	Days
Semi-major axis	0.0946	AU
Eccentricity	< 0.043	
Inclination	89.86	
Planet radius	1.730±0.025 $R_\oplus$	1 $R_\oplus$=6.957 × 10^8
Planet mass	5.60±0.19 $M_\oplus$	$M_\odot$=5.9722×10^{24} kg

2.2. Transit method

By using this basic information, just a few more information are needed to utilize the transit method. Many of the photometry already provide us with precise data for the transit on the spectrum, such as MEarth(first discovery), Spitzer, HST, TESS, JWST/NIRISS & NIRSpec(recent). The most precise data that has recently been collected, for example, the radius ratio of the planet and star, $R_p/R_\star$=0.0734, Transit depth δ≈0.00538=5380 ppm [5]. According to Dittmann, Jason A et. al from Cornell University, the Chile monitors nearby small M-dwarf stars for periodic dips in brightness that might signal a planet crossing in front of its star. Besides that, the rationale of this photometry is that each star is checked nearly every clear night since 2014, at ~30-minute intervals. If a possible dimming is spotted, the system can switch to high-cadence mode. The transit data that this photometry created can be seen in Fig. 1: Transit data from Chile monitor

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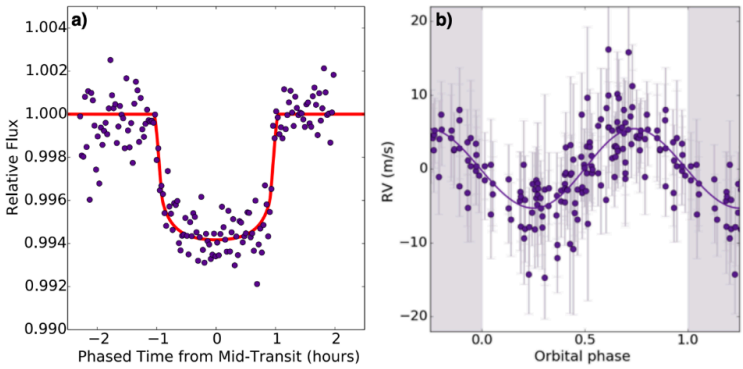


Figure 1. Transit data from Chile monitor [5]

Fig. 1 shows how LHS 1140 b was detected and characterized using the transit and radial velocity methods. In panel (a), the dip in stellar brightness marks the planet's transit across the star, and the depth of this dip indicates a radius of about 1.7 Earth radii. In panel (b), the sinusoidal radial velocity curve reveals the gravitational tug of the planet on its star, allowing astronomers to measure its mass. Together, these observations confirm that LHS 1140 b is a dense, rocky super-Earth. The data of LHS 1140 b's transit provides a fundamental foundation for the knowledge of the planet's properties. The recurrent dimming of starlight in the light curve of the left panel is a signal that the planet is moving directly in front of the host star from our Earth's line of sight. The depth of this dip is directly proportional to the square of the ratio of the radius of the planet to that of the star, allowing astronomers to calculate the physical size of LHS 1140 b. Its radius was thus discovered to be approximately 1.7 times that of Earth and is, therefore, a rocky super-Earth. The time between consecutive dips defines the orbital period, here approximately 24.7 days. This places the planet in the habitable zone of its quite cool M-dwarf host star, where temperatures might permit liquid water with suitable atmospheric conditions. Further, the shape of the transit curve—flat bottom and sharp ingress and egress—indicates a near-edge-on orbit, where the planet is moving almost through the center of the stellar disk, which maximizes the accuracy of the measurements. Together with the radial velocity curve shown in the right-hand panel, which provides an independent measurement of the planet's mass, the transit observations allow for a determination of bulk density. LHS 1140 b is discovered to be of a density of about 7.5 g/cm³, much higher than the Earth's mean, suggesting that there is a huge iron core and confirming that it is rocky in composition. Not only do the transit and radial velocity methods combined suggest the planet's presence, but they also calculate the size, mass, density, orbit, and potential habitability of the planet, making it one of the most promising candidates for atmospheric investigation with next-generation telescopes.

2.3. Radial velocity method

For the radial velocity method, the data for a spectrum for certain planets is needed, so it is possible to determine if the planet is moving away from or towards us. If there is a periodic wavelength shift on the spectrum, it means the planet is orbiting a star moving in a period. The radial velocity method is basically based on Doppler's effect. Doppler's effect is triggered by a moving object if it is moving away from or towards the observer. If the object is moving towards the observer, the frequency will be greater and the wavelength, therefore, will be shorter. As this effect is widely exhibited in the movement of planets, it can also be used in the detection of moving objects [6]. If the planet is moving away from the observer (people on the earth or a telescope like JWST/NIRISS

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to look at two transits, which successfully detect the blue shift and red shift), the red shift will occur because the longer wavelength, smaller frequency [7]. On the contrary, if the planet is moving towards the observer, a blue shift will be shown in the spectrum. Mathematically, using the sinusoidal curve is a way to determine the relative velocity, which is radial velocity, by the following formula:

$$\frac{\Delta\lambda}{\lambda 0} = \frac{\mathrm{vr}}{c} \tag{1}$$

This is the Doppler effect for light, Δλ is the change in wavelength, λ0 is the rest wavelength of the spectral line, vr is radial velocity (positive = moving away, negative = moving toward), and c is the speed of light.

Because of the very far distance, only a minute of wavelength shift can be detected. The spectrum of the exoplanet detection is too faint and tiny, so a very precise telescope and spectrographs like ESPRESSO/NIRP are needed. The spectrum provided by the ESPRESSO/NIRP is precise, but the data is too small to be shown in the graph, so I zoomed in on 100,000 points to show it in Fig. 2.

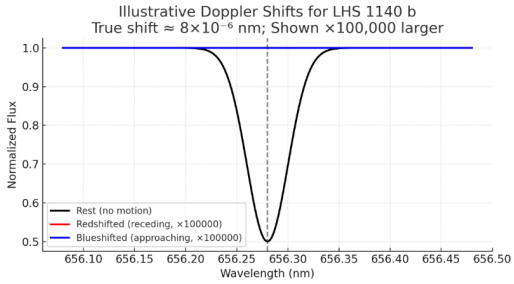


Figure 2. Spectrum amplified 100,000, showing the blue and red shift for LHS 1140 b (created by author)

Fig. 2 is an exaggeration to emphasize the shift in the spectrum. Obviously, the true shift for LHS 1140 b at K=3.8 m/s is only about 8×10-6 nm at H-alpha. In the plot, the lines are shifted by 0.83 nm (100,000× larger), so the red and blue curves are visible apart.

After using the precise telescope to determine the shift of wavelength in the spectrum, the relevant data, including the mass of the star, period of orbiting, and radial velocity, are all accessible, which can be plugged into the formula now. Then use the mass of the star and the radial velocity to deduce the mass of the planet. Therefore, the mass of the star LHS 1140 is 0.1844±0.0045 M⊙ ((3.67±0.09)×1029kg), and the radial velocity can be determined by the data in Table 2.

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Table 2. Radial velocity vs. phase of orbit for LHS 1140 b

Phase of orbit	Radial velocity (km/s)
0.201	0.003621
0.832	0.003307
0.565	0.001509
0.235	0.003783
0.661	0.003221
0.058	0.001354
0.758	-0.003795
0.465	0.000829
0.167	0.003295
0.913	-0.001975
0.047	0.001106
0.347	0.003116

Based on Table 2, these data can be plugged into a sinusoidal curve using the observed relationship between the phase of orbit and the radial velocity in the very far scope, but use the maximum point to determine the radial velocity (orbiting velocity using the curve). This can be explained with Fig. 3.



Figure 3. Observers from Earth observe the orbiting planet (created by the author)

It is widely known that the velocity vector will always be tangential to the orbit path. Observer, the telescope is near the Earth, so it is very distant from the target planet. It is hard to detect any motion perpendicular to the line of sight. The velocity that corresponds with the line of sight velocity, vr, can be measured. This essay previously talked about how using the wavelength change can determine this radial velocity. And the VR is changing when the phase is changing. But when the planet's component is completely equal to the actual radial velocity, it reaches the maximum or minimum point. That's why the sinusoidal curve can be used to determine the radial velocity. According to this, Fig. 4 is drawn.

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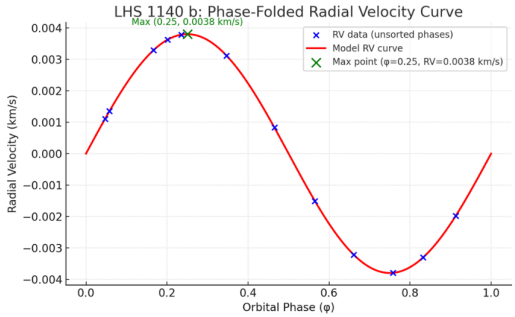


Figure 4. The sinusoidal curve for the radial velocity vs phase for LHS 1140 b (created by author)

According to Fig. 4, the radial velocity or orbit velocity is 0.0038 km/s. When getting the data of radial velocity, the mass of planet can be deduced. The key formula using here is:

$$M_{planet} = \frac{Radial\ velocity \times M_{star}^{2/3} \times Period^{1/3}}{(2\pi G)^{1/3}} \tag{2}$$

This formula comes from the standard radial-velocity semi-amplitude relation, and the derivation process is from Kepler's third law and the hypothesis of the relative mass. By using the radial velocity and mass of the star and period, it is easy to calculate the mass of the planet using the formula given that the radial velocity is 3.8 m/s, the mass of the star is (3.67±0.09)×1029kg, and the period from the Internet is 24.7369148±0.0000058 d((2,137,280.5±0.5) seconds). Now I will plug in the data I collected to see if this formula is eligible for LHS 1140 b:

$$M\ planet = \frac{3.8m/s \times (3.67 \times 10^{29}kg)^{2/3} \times (2{,}137{,}280.5s)^{1/3}}{(2\pi \times 6.674 \times 10^{-11}m^3kg^{-1}s^{-2})^{1/3}} = 3.35 \times 10^{25}kg \tag{3}$$

convert this mass to the unit of M⊕:

$$M = \frac{3.35 \times 10^{25}kg}{5.97 \times 10^{24}\ kg} = 5.61M\oplus \tag{4}$$

Comparing this data with the data previously collected from NASA, it can be seen that only a small deviation is from the true value, which validates the correctness of this radial velocity method in determining the mass of the planet.

3. Result and evaluation

Collect the data from above. Detection of the planets can be applied with the transit method and the radial velocity method. The idea of the combination uses the transit method to firstly detect the planet, and uses the radial velocity method to confirm the existence and calculate the mass. But two methods hold different standing points. Usually, the transit method is more universally applied. The reason is that the transit method is a method with more efficiency, scalability, and the wealth of information it provides from relatively simple observations. The transit method requires the precise measurement of a star's brightness over time. But it only requires the phase where the planet blocks the light from the star, which is exactly the mission of some telescopes like Kepler and TESS [8]. By contrast, the radial velocity method needs continuous observation, because from the spectrum and Table 2, it needs radial velocity over different phases, also the wavelength in different times, the data

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needs to be observed, and scientists need to determine the phase and including many factors, so the radial velocity method is obviously more tenuous and complex.

However, combining the transit method and radial velocity method to detect a planet is the inevitable choice. Because the transit method is used to detect the planets and later use the radial velocity to prove the correctness and gain extensive information, by first gathering their phase and velocity and deriving the mass, then further deriving the density according to the volume of the planet. And the data is now collected in Pulkovo Compilation of Radial Velocities (PCRV) [9]. However, there are a few drawbacks to transit methods and the radial velocity method, which is why it cannot be inclusive for all the planets that it can reach. For the transit method, the stellar variability will greatly impact the spectrum depth baseline. In more detail, Spots/flares add red noise; they can mimic depth or perturb baselines. And for the radial velocity method, this can only detect the movement that is away from or toward the observer. But if the orbital plane is a face-on, in other words, the component velocity is completely tangential to the line of sight, which means the observer cannot observe the movement of the planet. Also, in most cases, the movement is impacted by some unknown inclination angle, so only the component of wobble can be observed [10].

4. Conclusion

In this study, I use and compare the transit method and the radial velocity method in detecting planets. Firstly, I use the transit method and show the amplified graph to exaggerate the tiny redshift and blue shift. In the spectrum, the depth of the baseline indicates the existence of a planet, as well as revealing the wavelength and radial velocity of the planet. As for the radial velocity method, I find the data of radial velocity and phase of orbit, use a sinusoidal curve, and find the maximum point to determine the radial velocity (orbiting velocity), which is 0.0038 km/s. And use the formula using the data of stellar mass, time of orbit, and maximum radial velocity to calculate the mass of LHS 1140 b, which is approximately 5.61 $M_{\odot}$ Then I evaluate two methods, both of which have strengths and weaknesses. For transit, it is easier to observe and with high efficiency and a wider range. But it is not precise because the stellar movement can disturb the spectrum greatly. As for the radial velocity method, it can be very precise to determine the planet because it can be applied for most inclination angles. But the weakness of radial velocity can't measure when the plane is perpendicular to the line of sight. Future expectations on these two methods are positive, but discerning the problem of inclination, scientists also need to figure out how to compensate for each method for a more scientific and structural system. For instance, the transit method is effective in detecting the planet but the radial method holds higher precision and can deduce other relevant data in defining a planet.

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