The Transit Time Variations Investigation of Kepler-9

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Abstract

After the launch of the Kepler detector, more than 700 exoplanets, planets outside of our solar system, have been discovered. Most of these planets have been discovered by observing the transit of a planet as it blocks some of the light from the star around which it orbits. However, not all planets transit. The gravitational interaction between a non-transiting and transiting planet can lead to variations in when the transiting planet transits. These transit timing variations allow us to discover and characterize non-transiting planets. The goal of this project to model the transit timing variations of exoplanets within Kepler-9, via simulation. Applying the same method as former scientists adopted, this paper will include analysis the Kepler–9 system and get its period and general characteristics, like density, of the two planets, Kepler-9b and Kepler-9c. Plus, compared to other existing research, what may contribute to the difference in the obtained data will also be evaluated in this paper.

Keywords

Transit Timing Variations (TTVs), Kepler-9, Kepler-9a, Kepler-9b, Kepler-9c.

1. Introduction of Transit Timing Variations

1.1 Transit time variation

1.1.1 Definition of transit

An exoplanet must pass through its host star with respect to one particular point. This will cause a change in the decrease of the amount of observable flux (magnitude of energy transmitting through the one-unit area). So, the result of transit is a decrease in the observable flux from the star because the planet is blocking some of the star’s light.

1.1.2 Implication of the transit time variation

By observing transits, scientists could detect more than 700 little exoplanets, since the decrease in flux is much easier to detect than just looking for existing exoplanets [1]. So, with Kepler’s third law, knowing the period of one astronomical object orbiting one star, it is possible to come up with an approximation of the semi-major axis of that orbit. Then, using the formula of gravitation and detecting the radial velocity of the transit, the mass of that object could be obtained. Plus, with the help to detect the change in flux, the radius of the planets could be obtained. Thus, it is feasible to finalize the density of that planet.
1.2 Factors influence TTV

1.2.1 General description

The distance between celestial bodies needs to be the same, as long as the system could ensure the gravitational pull could remain constant. Thus, the orbital speed could be the same throughout the simulation.

1.2.2 Other factors, apart from ones that could influence gravity

a) Diameter

According to the definition of transit, an astronomical object must block lights from its host star, to affect reducing flux. Thus, the diameter of the approaching astronomical objects is essential for blocking the light emitted by the host star. The formula is the following:

\[
\Delta F = \frac{R_p^2}{R_*^2}
\]

In this formula, the magnitude of changes in flux is caused byRp, the diameter of the planet, and R*, the diameter of the host star. So, to not let this be a disruptive factor for the final result, diameters of stars and planets will be a control in the experiment.

b) Tilt

Tilt, also known as obliquity, is the difference in angle between one’s rotational axis and orbit’s direction. If the obliquity is zero, it means it could be considered as a self-rotating object moving in a horizontal plane, with respect to its rotational axis. Tilt, as essential astronomical characteristics, is also an important factor which could influence the transit time variation for an exoplanet. For planets that have a high tilt angle, the transit time variation would be larger, and vice versa [2]. Thus, this will also be a control in the experiment to ensure this one will not influence the final observation, even though it will not a dominant factor in our experiment.

1.3 Selection of the three-body system

The system selected for the simulation is the system of Kepler-9, Kepler-9b, and Kepler-9c. The reason to select this system is that Kepler-9b and Kepler-9c are quite large in mass and radius, comparing to other exoplanets systems’, which are approximately 0.842 of the radius of Jupiter and 0.823 of the radius of Jupiter, respectively [3]. Thus, using these sets of data, a clearer relationship could be obtained, due to the large attraction caused by larger mass.

2. Introduction of Kepler-9 System

Kepler-9 system was discovered in 2009 between May 13 to May 16 by the usage of 29,246 exposures through a broad optical bandpass[1]. Kepler-9 system is constituted by the other two big planets named Kepler-9b a Kepler-9c respectively. Although there is a third planet called Kepler-9d (KOI-377.03) in this system, due to its small scale (approximately 1.6 R⊕), it could not bring an obvious effect for the TTVs between Kepler-9 and itself; thus, it is discarded in our study.

The orbital period of Kepler-9b and Kepler-9c are 19.24 and 38.91, suggesting that \( P_c/P_b=2.203 \), indicating the system is probably affected by a 2:1 mean motion resonance (MMR)[1]. Although the period parameter is not included instead of directly using mass for simulating the TTVs is considered, it would be significant to know the period of these two planets as its period could help explain the TTV data while doing the comparison.

Both Kepler-9b and Kepler-9c are categorized as brown dwarfs, in which their mass are 0.25 and 0.14 times of the mass of Jupiter[1], suggesting they are gas giants but similar to or small and less than the scale of Saturn. The probability of these two planets to simultaneously transit is low due to their inclination which is estimated between 2° and 10°.
3. Methodology and Data Collection

Due to the limitation of equipment, our research team has difficulties to gather the data of Kepler-9 through direct observation by radio telescope, so the data of Kepler-9 are mainly gathered online based on former researches. The general data of Kepler-9 is shown below:

<table>
<thead>
<tr>
<th>Star</th>
<th>Kepler-9/ KOI-377/ KIC 3323887</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Yellow dwarf</td>
</tr>
<tr>
<td>Distance</td>
<td>7566361.19 km</td>
</tr>
<tr>
<td>System diameter</td>
<td>0.49 AU</td>
</tr>
<tr>
<td>Mass</td>
<td>1 M☉</td>
</tr>
<tr>
<td>Apparent mag</td>
<td>−33.921</td>
</tr>
<tr>
<td>Absolute mag</td>
<td>4.986</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.96789</td>
</tr>
<tr>
<td>Temperature</td>
<td>5488.9 °C</td>
</tr>
<tr>
<td>Number of planets</td>
<td>3</td>
</tr>
</tbody>
</table>

A python program (see in Appendix 1) is written for simulating the ttvs between a star and an exoplanet, which is applicable for analyzing the ttvs of Kepler-9 and Kepler-9b. What demonstrates below is the data of Kepler-9 input.

```
mass of star(solar mass):1
radius of the star(solar radius):1.1
mass of planet1(Earth mass):80.136
mass of planet2(Earth mass):54.378
distance from star to planet1(in AU):0.140
distance from star to planet2(in AU):0.225
the tilt of planet1 in degree:0
the angle observed by sun between the viewer and the planet1 transit point in ecliptic(0 if transit can be observed):0
the tilt of planet2 in degree:0
the angle observed by sun between the viewer and the planet2 transit point in ecliptic:0
how many day one step(can enter small number like 0.01 for accurate transit time):0.001
the total time(day):10000
planet1:red  planet2:blue
```

Fig.1: Data of Kepler-9 input for the python simulation

4. Presentation of Data

After plugging the data of Kepler-9b and Kepler-9c into the python program, the pathway of these two planets while transiting could be shown; what represented below is the data that are plug in.
Table 2: Data of Kepler-9&9b&9c plug into the program [1]

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of the star (solar mass) [Kepler-9]</td>
<td>1</td>
</tr>
<tr>
<td>Radius of the star (solar radius) [Kepler-9]</td>
<td>1.1</td>
</tr>
<tr>
<td>Mass of planet1 (Earth mass) [Kepler-9b]</td>
<td>80.136</td>
</tr>
<tr>
<td>Mass of planet2 (Earth mass) [Kepler-9c]</td>
<td>54.378</td>
</tr>
<tr>
<td>Distance from star to planet1 (in AU) [Kepler-9b]</td>
<td>0.140</td>
</tr>
<tr>
<td>Distance from star to planet2 (in AU) [Kepler-9c]</td>
<td>0.225</td>
</tr>
<tr>
<td>The tilt of planet1 in degree [Kepler-9b]</td>
<td>0</td>
</tr>
<tr>
<td>The angle observed by sun between the viewer and the planet1 transit point in ecliptic (0 if transit can be observed) [Kepler-9b]</td>
<td>0</td>
</tr>
<tr>
<td>The tilt of planet2 in degree [Kepler-9c]</td>
<td>0</td>
</tr>
<tr>
<td>The angle observed by sun between the viewer and the planet2 transit point in ecliptic (0 if transit can be observed) [Kepler-9c]</td>
<td>0</td>
</tr>
<tr>
<td>How many days one step</td>
<td>0.001</td>
</tr>
<tr>
<td>The total time (days)</td>
<td>10000</td>
</tr>
</tbody>
</table>

Tilt and angles are assumed to be 0

The graph to demonstrate the pathways of these two planets could be represented as a cosine-like curved shape, which are demonstrates below.

![Fig.2: Generic graph formed by the simulation](image)

The movement of the blue dot at the top of the graph could be represented as:

\[
line x = 1290 \cos \left( \frac{2\pi}{6.98 \times 10^{-8}} x \right) + 6.726 \times 10^6
\]

The zoomed line is represented below to show this relation:
The movement of the red dot in the middle of the graph could be represented as:

\[
line\alpha = 602\cos\left(\frac{2\pi}{6.98\times10^{-8}\alpha}\right) + 1.6514 \times 10^6 \\
line\beta = 301\cos\left(\frac{2\pi}{6.98\times10^{-8}\beta}\right) + 1.6511 \times 10^6
\] (3) (4)

The zoomed line is represented below to show this relation:

The basic form is:

\[
\text{Line}() = (\text{constant})\cos\left(\frac{2\pi}{6.98\times10^{-8}} - 8(\ )\right) + \text{constant} \times 10^6 \\
\text{Line}() = (\text{constant})\cos\left(2\frac{\pi}{6.98\times10^{-8}} - 8(\ )\right).
\] (5) (6)
The movement of the blue dot at the top of the graph and red dot is that the constant about the
the red dot after the plus sign is close to $1.65 \times 10^6$.
In the end, two lines that represent the TTVs of two Kepler-9 planets are simulated. The graph of
time against its luminosity strength is demonstrated below.

![Graph of time against its luminosity strength](image)

**Fig.5: Zoomed bottom TTVs lines of two planets on the graph**

### 5. Analysis

Unfortunately, the transit timing variation line for Kepler-9b is flawed because it represents an
irregular trend line while doing the simulation. Our team hypothesized that the tilt may be a possible
factor that caused the irregular mode of the transit timing variation of; however, after adding the tilt
of 6 degree, which is the average estimated tilt of the Kepler-9b, the graph still represents an irregular
mode of the transit timing variations.

![Before adding the tilt](image)
![After adding the tilt](image)

**Fig.6: Before adding the tilt**  **Fig.7: After adding the tilt**

Due to the reason of both technique problem and time limitation, our group decides to discard the
data of Kepler-9b and only focus on analyzing the result of Kepler-9c.
The result of transit timing variations of Kepler-9c shows a regular mode (cosin-like graph), which
suggests every transit timing variation of Kepler-9c follows such a regular patter.
The result of the simulation demonstrates that the time taken is demonstrated below:

\[
Tc = (0.164 - 0.069) \pm \left( \frac{0.091-0.055}{2} + \frac{0.186-0.142}{2} \right) / 2
\]

\[
Tc = 0.095 \pm 0.02 \text{ (unit: days)}
\]

Then comparing the result to the actual transit timing result formed by scientists working for the Kepler mission.
The actual $T_c$ demonstrates on the graph is:

$$T_c' = 0.105 + 0.102 = 0.207 \text{ (unit: days)}$$

Comparing to the actual result of 0.207 days, even our maximum simulated result which is 0.095+0.02=0.115 is far from 0.2. Clearly, the result from simulation could not well-fit the actual result. This leads us to do our reflection.

6. Reflection on Limitation

The process of writing the python program is complex, especially when tilt was added in. In order to enhance the accuracy of the program, the usage of the tilt is discarded even though it is written it because the lack of applicability and accuracy of the tilt codes due to its complexity. Though assuming tilt as 0 to eliminate the effect of tilt could guarantee the accuracy of the whole code, the simulated result may not well fit the actual data since the uncertainty of the universe is also complex [4]. The discard of tilt may lead results to form the inaccurate result of Kepler-9b data and cause its irregular pattern to take place. So, later to improve both the accuracy and precision, the part of tilt in the program should be review carefully to be guaranteed for its accuracy so that the tilt could be applied to make precise data to model the situation as real as possible.

Besides, the reason why Kepler-9c’s simulated transit time could not match the actual result is that our group did not consider the influence of the star’s atmosphere. It should be noticed that the transit begins while a planet enters the sphere of star’s atmosphere, rather than beginning at when the planet has covered completely surface of the star. The atmosphere (e.g. photosphere, chromosphere, and solar corona) of a star can also illuminate the light, and when a planet is a transit to the atmosphere of a star, it can also block the light and lower the luminosity of a star [5]. If the effect of the atmosphere is removed from the actual Kepler-9c transit timing variation graph, then our simulated data could fit the actual data.
The actual $T_c$ demonstrates on the graph while discarding the effect of the atmosphere now is:

$$T_c'' = 0.065 + 0.065 = 0.130 \text{ (unit: days).}$$  \hspace{1cm} (10)

Now comparing to the simulated data (0.115 days) to the actual data (0.130 days), the relevance is increased as the effect of the atmosphere is discarded. So, later to improve the accuracy of the simulated data, the factor that the atmosphere can also emit light should be considered into our simulating program.

7. Conclusion

Through this paper, the regular transit timing variation could be modeled through our specially designed program. The period, density, and volume of the two Kepler planets could be correlated subsequently. Furthermore, in future research, the flaw in programming discussed in the limitation part could also be used to analyze its effect on other related topics, like two other Saturn candidates, KOI-377.01 with a 19-day period and KOI-377.02 with a 39-day period [6].

References


