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Testing the Obliquity-Tide Hypothesis and the Potential Companion for the Orbital Decay of WASP-12b

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Abstract. The hot Jupiter WASP-12b exhibits rapid orbital decay, with its period shrinking at a rate of approximately 0.03 seconds per year, faster than predicted by standard stellar tidal dissipation models. An alternative theory proposes that this decay is driven by obliquity variations induced by a nearby companion planet, predicted to produce a radial-velocity (RV) signature of 7 m/s. This research aims to test the existence of the potential companion using RV data obtained from SOPHIE, HIRES, HARPS-N and NEID. A model combining orbital and tidal effects is built to search for companion signals, and the residuals are analyzed with a Lomb–Scargle periodogram. At the same time, the BLS algorithm is applied to TESS light curve data, after masking out the transits of WASP-12b, to search for additional transit signals. The RV data analysis suggests that the most likely companion period, if it exists, is approximately 0.789 days, which is inconsistent with the TESS data result of 0.728 days. While both results have statistical significance and acceptable uncertainty, the cause of the difference between the two periods needs further exploration and explanation.

Keywords: WASP-12b, orbital decay, planetary companion, radial velocity analysis, tidal effects on radial velocity, planetary period

1. Introduction

WASP-12b is an inflated transiting hot Jupiter that orbits a G0-type main-sequence star with a period of 1.091 days and exhibits strong star–planet interactions. With a mass of about 1.41 Jupiter masses and located only 0.02299 AU from its host star, its spin and orbital periods are expected to be tidally synchronized. The proximity between WASP-12b and its host star can significantly affect both the stellar and planetary atmospheres, causing atmospheric expansion, nonuniform temperature distribution, and tidal bulges on the star and planet. Those tidal bulges are the result of the long time stretching by the tide-generating force, which is the resultant force of the gravitational force and the inertia force of the star-center reference system between the star and the planet. As a result, both WASP-12 and its planet take shape as the two-sided bulges (ellipsoidal shape). Consequently, the period of radial velocity variations due to the tidal effect is exactly half of the orbital period.

Since its discovery in 2008 [1], WASP-12b has become an important laboratory for exoplanet research, focusing on tidal effects, mass loss, and orbital evolution [2,3]. The star's high brightness

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and the planet's ultra-short orbital period enable highly precise measurements of radial velocity, transit duration, and other parameters, making WASP-12b a particularly valuable target. Furthermore, transit timing observations indicate that WASP-12b is experiencing orbital decay at a much higher rate than expected [4,5,6]. The equilibrium tide model cannot provide a satisfactory explanation, and several alternative hypotheses have been proposed, including apsidal precession, dynamical stellar tides, and magnetic braking [7,8]. Among these, the obliquity tide mechanism is especially significant: if WASP-12b maintains a spin–orbit misalignment, interior energy dissipation would be intensified, sustaining the observed orbital decay. Moreover, its high obliquity could be maintained by a close-in companion through resonance [9].

This paper aims to test the obliquity tide hypothesis by searching for the predicted close-in companion. We searched for both periodic light-curve fluctuations and periodic RV signals that might be produced by the companion. The predicted parameters of the companion are as follows: it has approximately 10.6-14.2 Earth mass; transit duration is about 0.03-0.06 phases; its radius is about 3.5-4 Earth radius; transit dip is about 0.0386-0.0504 percents. We use RV data from SOPHIE, HIRES, HARPS-N, and NEID, and apply the Lomb–Scargle periodogram to analyze potential periodic signals in RV residuals. In addition, we apply a transit mask to filter out the signal of WASP-12b from the Transiting Exoplanet Survey Satellite(TESS) data and then use the BLS algorithm to explore potential additional transit phenomena. TESS is a NASA astrophysics explorer mission selected for launch in 2017, and it operates in a highly elliptical 13.7-day Earth orbit and, during its two-year prime mission, uses four 10-cm optical CCD cameras perform precise photometry over a 24x96 degree field of view [10].

The structure of the paper is as follows: Section 2. presents the data analysis; Section 3. describes the methodology and results; Section 4. provides the discussion; Section 5. is our conclusion.

2. Data

Given that RV measurements can detect the motion of host stars of nearby planets with high sensitivity to short orbital periods, while also providing direct physical constraints on planetary gravitational influence through their well-established parameter space and technical maturity, we employed an RV model and extracted data from the following sources (Table 1). Our original data set has 183 data points which are recorded by four different instruments which is NEID, SOPHIE, HIRES and HARPS-N in four distinguished regions.

The instruments and their sources: NEID (Unpublished data from J. Winn), SOPHIE [1], HIRES [5], HARPS [11], [12].

To confirm the existence of the planet via Doppler shifts in stellar spectra, we selected long-term RV data of WASP-12 from the aforementioned literature. The different instruments recorded their data on different absolute velocity scales. Thus, the only meaningful quantities for this study are the differences in velocity observed by a single instrument. We create an additive offset to measure the differences in the scales in these instruments.

In the next step, we will gather information on parameters measured by leading research groups and identify the sources of these data, which is helpful to construct our model in the next section.

The TESS data used in this study comes from Sector 20, 43, 44 and 45, with an exposure time of 120 seconds per observation, with an author Science Processing Operations Center(SPOC).

For further analysis, we employed two distinct methods to identify periodic signals in the RV and TESS datasets, respectively. Specifically, we used the Lomb-Scargle periodogram (L-S) to analyze the RV data. The L-S method, based on Fourier transform principles and the least squares approach, enables the detection of periodic signals based on an unevenly spaced time series. By fitting the data

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Table 1: System Parameters of WASP-12b.

Parameters	Value (Uncertainty) and Unit	Sources
Period (P)	1.091419649(25) days	[5]
Mid-transit time (t_c)	2456305.455521(26) TBJD	[5]
Transit Duration (T)	0.122(1) days	[1]
Radius ratio (R_p/R_s, k)	0.1170(2)	[13]
Scaled semi-major axis (a/R_s)	3.00(2)	[13]

with a combination of sine and cosine functions across a range of periods, the method identifies the most probable period and quantifies the fit as a power value between 0 and 1. For the TESS data, we applied the Box Least Squares (BLS) method. BLS is a technique that uses a rectangular function to fit small light dips in the TESS data. During a BLS search, many trial values are considered for the period, phase, and duration of the dips. This method is particularly sensitive to short-duration transit-like signals in noise, enabling quick identification of potential transit events.

From the radial velocity data recorded by the 4 instruments (Figure 1), we fold the data with the period of WASP-12b (1.091419649 days) in Table 1 and obtain a sinusoid pattern (Figure 2). This signal is dominated by the reflex orbital motion of the star in response to the planet's gravitational pull. We fit a model basically by a sinusoidal function with a phase which is defined as $\phi = \frac{2\pi}{P}(t - t_c)$.

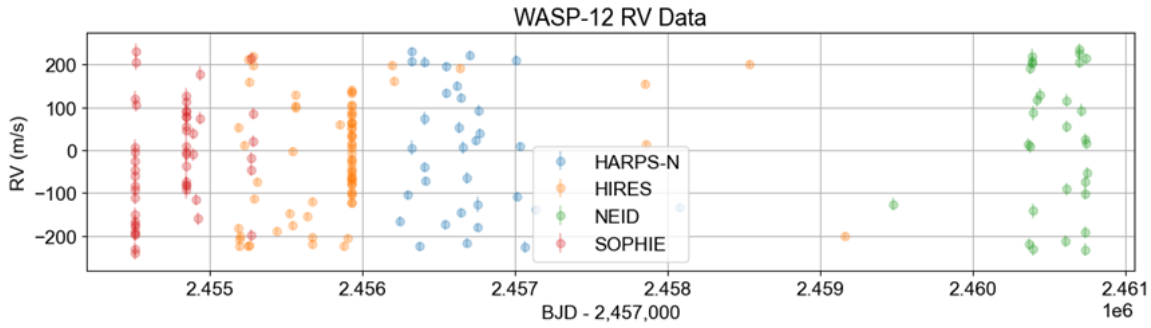

Figure 1: The figure shows the original radial velocity data between the time 2,459454 and 2459461 in TBJD by the four instruments (HARPS-N, HIRES, NEID and SOPHIE).

We also decided to omit from consideration the RV data that were obtained during transits, in order to avoid the unnecessary complication of modeling the Rossiter-McLaughlin effect [14]. During the transit, the radial velocity exhibits a characteristic S-shaped shift due to the selective blockage of the star's rotating surface. This effect introduces a deviation when fitting data, as the presence of these shifted data points can skew the resulting model.

In the next section, we will outline the detailed process of analyzing the data, describing how we identified periodic signals using the dataset mentioned and two distinct methods.

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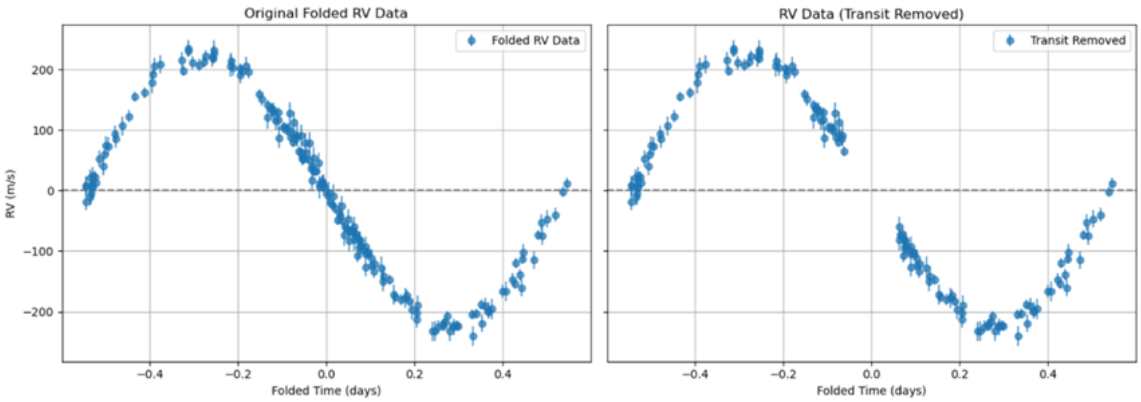

Figure 2: The left graph is the apparent RV as a function of our folded time. The right graph is the remaining data after eliminating the data obtained during transits, the region centered on phase 0.).

3. Methods and Results

Based on the data described in the previous section, we modeled the radial velocity using a physical model adapted from [7], which consists of two sinusoidal terms and a constant:

$$RV(t) = -K_{\text{orb}} \sin(\phi) + K_{\text{tide}} \sin(2\phi) + C_i. \tag{1}$$

The negative sign in front of the first term is introduced because the star is accelerating toward the observer at the time of transit. Since the planet is tidally locked and moves away from the observer in its orbit, this causes the star to distorted into a slightly ellipsoidal shape due to the gravitational force of the planet. As a result, both the star's brightness and its net apparent radial velocity vary periodically with a period of P/2. This is because of the axial symmetry of the star, where its sky projection at time t looks the same as at time t + P/2 like the Figure 3. The star moves closer to the observer at the midpoint of the transit, opposite to the planet's motion, and this leads to the tidal bulge receding accordingly. Consequently, the K_{orb} and K_{tide} terms are in opposite signs, with the tidal period being half of the orbital period, approximately 0.545 days because of the ellipsoidal deformation of the star when the tidal bulge formed like Figure 3. ϕ represents the phase of the period, and we define t_c as the origin of the radial velocity curve, since at this point, both K_{orb} and K_{tide} are zero, as they are perpendicular to the line of sight.

After constructing our model, We fit this model with the data shown in Figure 2. To account for instrumental offsets, we construct an additive offset to mitigate scale differences among instruments.

It is clear that when the radial velocity reaches its highest amplitude, the contribution of the tidal term should be zero. This is because t_{c} serves as the reference point for both terms, and the tidal period is approximately half of the orbital period. Therefore, when calculating the maximum point of the total model after fitting, it should exactly to the K_{orb} value in the equation 1. By identifying the maximum turning point of the smoothed fit curve, we can extract the K_{orb} value, which is found to be 224.88 m/s.

After constructing our model, Our model yields a tidal amplitude with approximately $7.94 \pm 1.26 m/s$, which is consistent with the value of 7 m/s reported by [9]. The χ^2 of our model demonstrated in figure 4 is 142.19 with 142 data points and 4 variables (reduced χ^2 about 1.04). We also quantified the relative instrumental scaling factors with respect to HARPS-N, along with their uncertainties, as summarized in Table 2.

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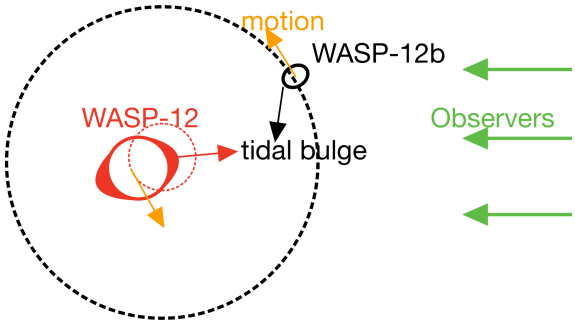

Figure 3: Schematic diagram about the tidal synchronization and its tidal bulge, the black dashed line is the orbit of the planet and the red dashed line is the orbit of the star, the orange arrows symbolize it velocity at that moment. (Diagram is not to scale).

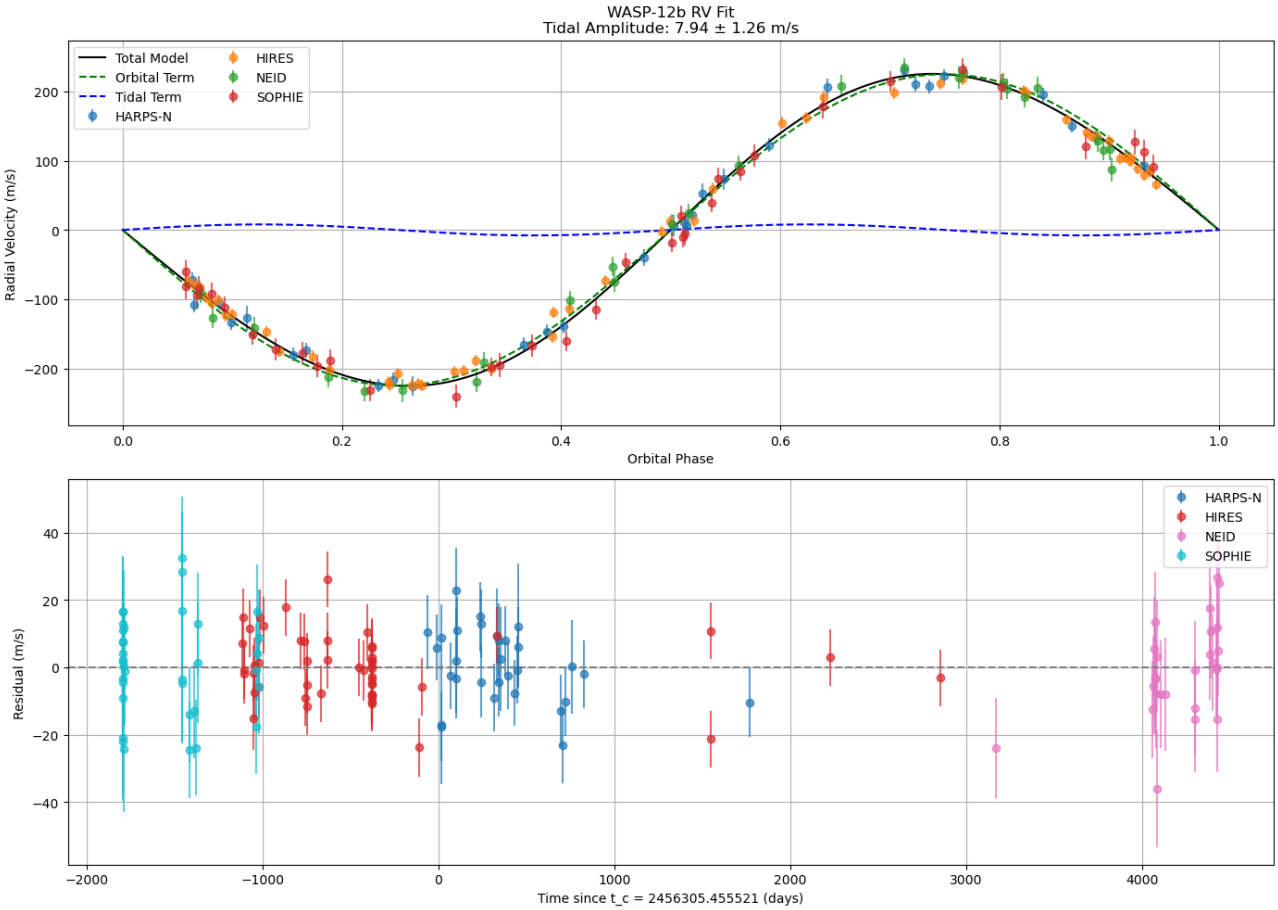

Figure 4: The data are shown along with the components of the best-fit model, obtained by performing least-squares fitting of the data with the function given in equation 1. We isolated and plotted the tidal term by using subtracting the orbital component of the model from the total model. The remaining residuals are plotted as well.

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Table 2: Instrument velocity offsets (in comparison with HARPS-N).

Instrument	Value (m/s)
HARPS-N	-0.27 ± 2.06
HIRES	2.21 ± 1.20
NEID	1.09 ± 2.97
SOPHIE	-2.50 ± 2.74

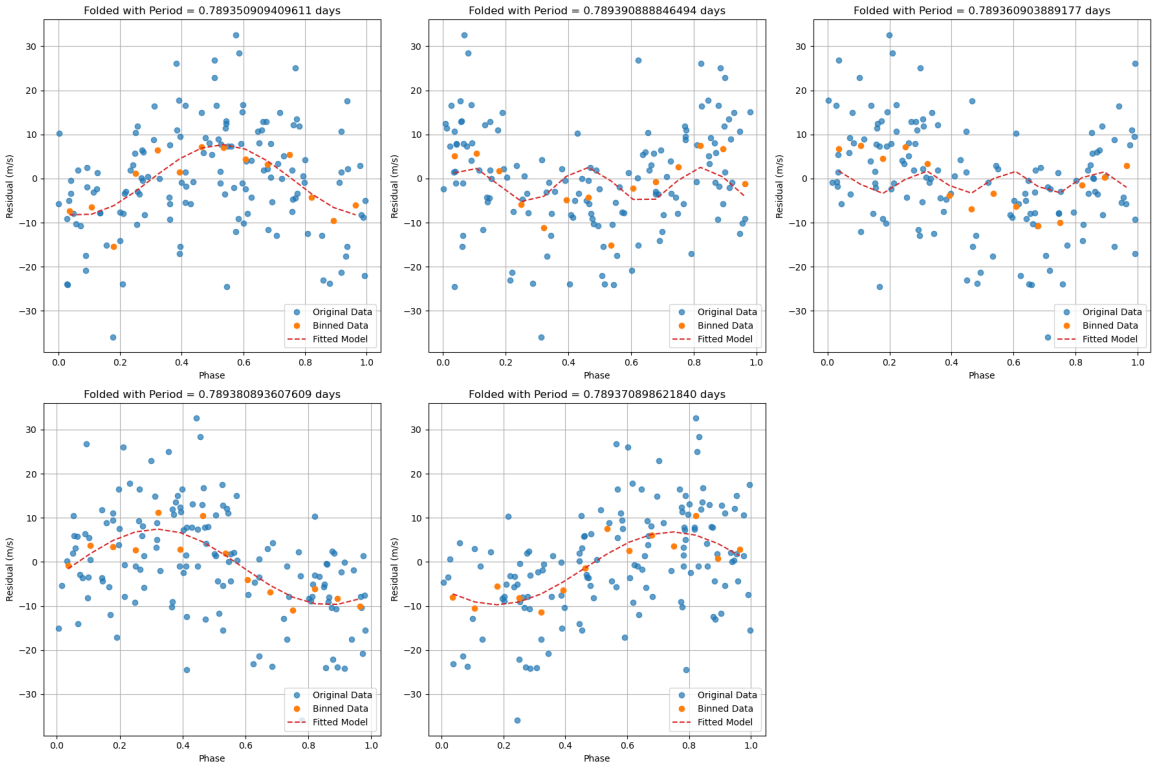

Figure 5: the folded graph by the targeted periods and the binned points with fitted model.

To identify the most likely period in the residuals and confirm the presence of periodic signals that are independent of the tidal and orbital terms, we we employed use the Lomb-Scargle periodogram method. This method involves constructing a sine function with varying frequency or period and evaluating how well the data align with the function when folded with the targeted period. The fit quality is measured as the power, a measure of the degree to which the variance in the data can be explained by a sinusoidal function. A peak in the power spectrum may indicate a potential companion period. We print out the five periods with the top 5 powers that are recorded in Table 3, and show the corresponding power distribution and folded light curve in Figures 6 and 5, and the x-axis is zoomed in Figure 7.

The slight variation among these values arises because the targeted period is very specific, even a small interval between adjacent points can lead to significant power deviations. Since then, we only consider the highest power one.

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Table 3: The top five possible periods of the residuals.

Periods (days)	Power [0–1]
0.789370909409611	0.25021
0.789380888846494	0.24406
0.789360903889177	0.23518
0.789390888846494	0.21925
0.789350909409611	0.20187

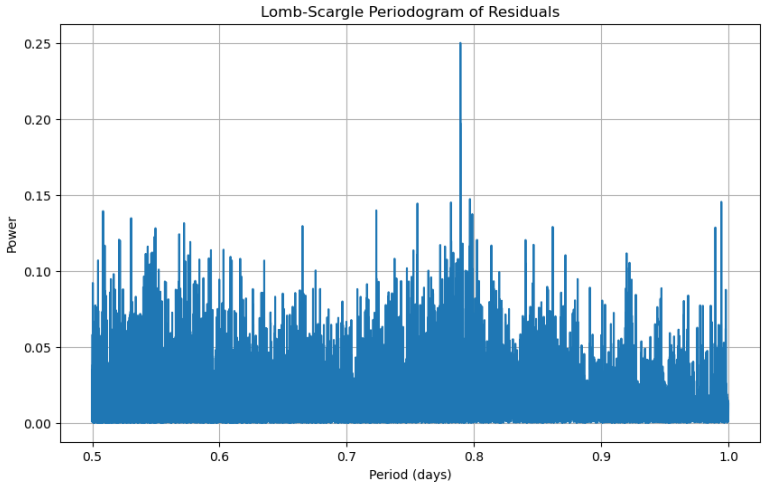

Figure 6: Searching for the possible periods of the companion by Lomb-Scargle method.(the peak in that graph is about 0.789 days)

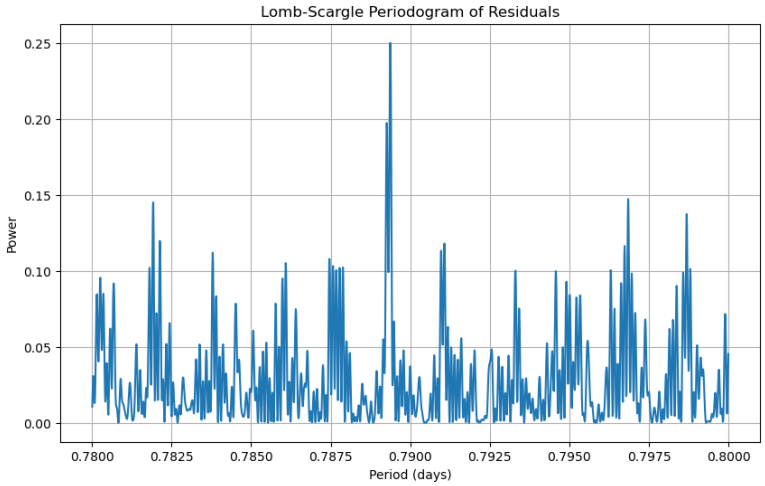

Figure 7: Searching for the possible periods of the companion by Lomb-Scargle method from 0.78 to 0.8 days.

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In Figure 5, a periodic pattern similar to a negative sine function is evident. To verify its authenticity, we performed a statistical test. After fitting the model, the possibility that the signal arose from random noise was evaluated through pure noise simulations. These simulations used the same time sampling and model parameters as the observations, with random noise from a Gaussian (normal) distribution with the mean of data set = 0 and standard deviation equal to the typical error bar of the data from that instrument. A total of 10,000 realizations were produced and for each case, the Lomb-Scargle periodogram was calculated to identify significant periods attributable solely to noise. The 95 percent and 99 percent significance thresholds derived from the resulting maximum power distribution are shown as reference lines in Figure 8.

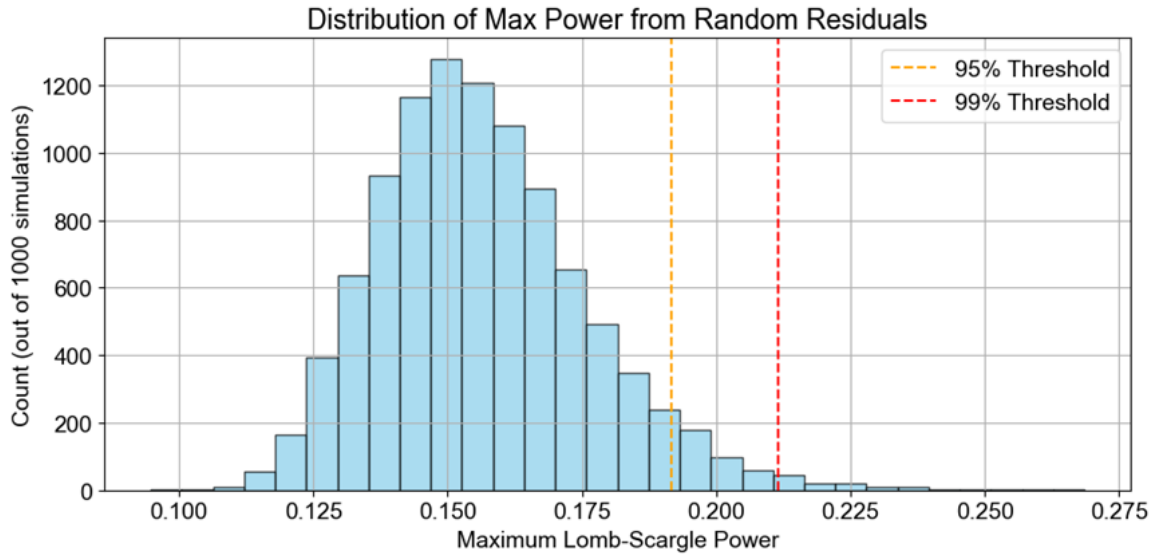

Figure 8: Distribution of the maximum Lomb-Scargle power from 10,000 random realizations and the thresholds of 95 percent and 99 percent.

From Table 3, we obtain a power of approximately 0.25, which exceeds the significance threshold of 99 percent, indicating a deviation from the expected behavior of pure random noise. This suggests that the detected periodic signal may be genuine due to its distinct power relative to the remaining powers. Moreover, the period around 0.789 shows no obvious commensurability with the orbital period, arguing against an origin in tidal effects.

According to [9], the obliquity tide model predicts that WASP-12b may host a companion with a mass of $M_2 \sim 10 - 20\ M_\oplus$ and a semi-major axis $a_2 \leq 0.04$ AU. Using the standard mass function and the parameters derived in this work—namely a period $P = 0.78937$ days and a maximum radial velocity amplitude shown in Figure 5, which is about 6-8 m/s—we further assess the likelihood of such a companion.

$$M_p \sin i = \frac{K M_* P}{2\pi (G M_*)^{\frac{1}{3}}} \times \left(\frac{2\pi}{P}\right)^{\frac{2}{3}} = K \left(\frac{P M_*^2}{2\pi G}\right)^{\frac{1}{3}}. \tag{2}$$

From this calculation, the minimum possible mass of the potential planet (companion) is estimated to be $6.354 \times 10^{25} - 8.472 \times 10^{25}$ kg, corresponding to approximately $10.6 - 14.2\ M_\oplus$. This result

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supports the initial prediction of the potential companion with a period of 0.78937 days. Furthermore, based on this period and a plausible range of impact parameters, the expected transit duration in phase units is estimated between 0.03 and 0.06.

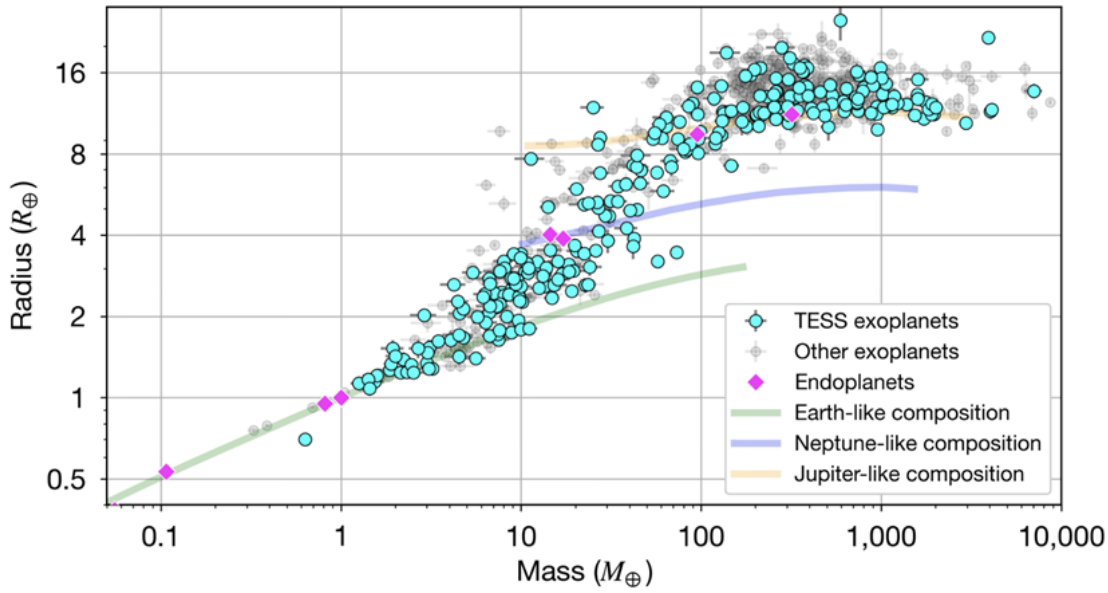

Figure 9: the Mass and Radius relationship of the exoplanets.(J. Winn, personal communication, using data from the NASA Exoplanet Archive)

From Figure 9, the companion's radius is estimated to be approximately $3.5 - 4.0\ R_\oplus$, consistent with a Neptune-like planet capable of inducing an obliquity in WASP-12b. In addition, using Equation (3), the predicted transit depth is calculated to be about 0.0386-0.0504 percent.

$$\delta = (\frac{R_p}{R_*})^2 \tag{3}$$

An aperture mask was applied to exclude light curve data associated with WASP-12b, and the remaining data were analyzed using the BLS method. This technique employs a small box-shaped model to identify potential periodic flux dips in the time series. From this analysis, we detected a period of 0.728503 days with consistently high BLS power across all available TESS data sets (Figure 10). However, this period does not match the value obtained from our radial velocity analysis. The 0.728503 days signal is close to two-thirds of the orbital period, suggesting that it may represent an artifact induced by tidal effects or a coincidental alignment.

The modeled light curve allowed us to construct an expected transit profile using a simple box function with the parameters of the flux change and the transit duration of the potential companion (neglecting limb darkening) as an expected dip and compare it with the fitted curve derived from the TESS data. However, no corresponding signal was identified in this comparison (Figure 11).

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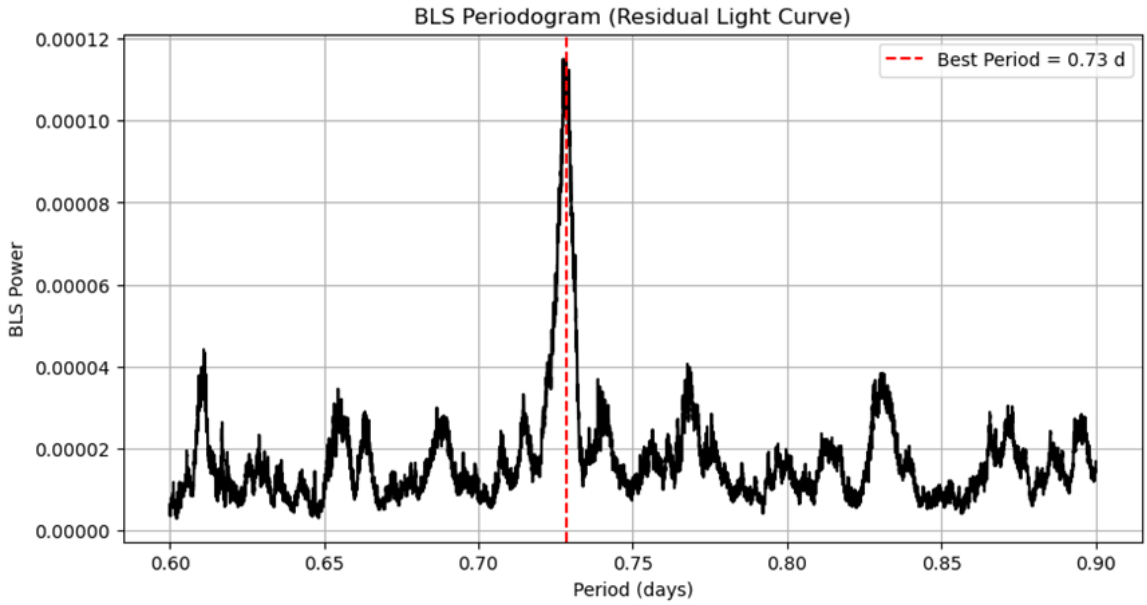

Figure 10: The period obtained by using the BLS method and found a period with a BLS power higher than 0.0001 (Data from TESS sector 20).

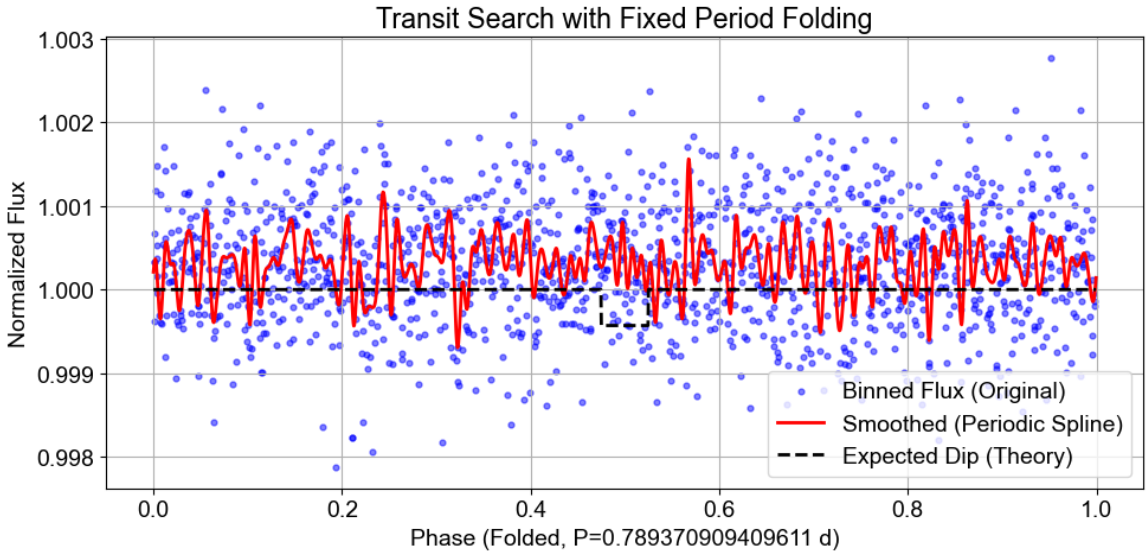

Figure 11: the comparison between the expected dip and the fitted curve.

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4. Discussion

The discussion part focuses on comparing the two different methodologies used to analyze the possibility of a companion in the WASP-12 exoplanet system and making further inferences.

In the RV analysis, we removed the dominant signal—WASP-12b—from the observed RV data and built a model to fit the residuals. The results, discussed earlier, indicate that the most prominent periodic signal is about 0.789 days, with sufficient statistical significance to suggest the possible existence of a companion planet. By contrast, analysis of the TESS light curve, after masking WASP-12b's transit and applying the BLS algorithm, yielded a candidate period near 0.728 days, close to two-thirds of WASP-12b's orbital period. However, tidal synchronization, noise, and the lack of predicted transit dips consistent with RV expectations weaken the case for a detectable companion.

There are several potential reasons for the absence of a transit signal even if a companion exists. First, the companion could have an impact parameter too large to allow the possibility of transits. Second, the companion might have a small radius, making the transit depth fall below the TESS sensitivity threshold. Consequently, the light curve data cannot provide strong evidence to support the RV-based findings. A method known as Transit Timing Variations (TTV), as introduced by [15] and [16], has been employed to observe variations in transit times that arise due to the gravitational influence of an additional planet, even in the absence of direct transits. When transit timing deviations caused by orbital decay become evident, it becomes possible to identify periodic fluctuations in the observed transits of the planet, WASP-12b. This approach offers a promising avenue for future research in the WASP-12 system, potentially shedding light on the existence and characteristics of a companion planet.

Based on the analysis presented, we conclude that the RV results point to a plausible companion whose parameters are broadly consistent with [9], supporting the tidal dissipation model. Although TESS data yields no additional transit evidence, we cannot rule out the possibility of its existence due to limitations in transit detection. In the future, high-precision photometry from missions such as PLATO or JWST, or extended high-quality RV datasets, will allow us to test the companion hypothesis with greater confidence.

5. Conclusion

In this study, we applied two independent period-detection methods and derived a tidal amplitude of approximately 7.93 ± 1.25 m/s, a result consistent with the previous work by [9]. Additionally, we identified a new period of about 0.789, which is unrelated to tidal effects or orbital radial velocity. Our mass estimate of 17.7 $M_{\oplus}$ based on this period falls within the range predicted by [9]. However, in the TESS data from sectors 20, 43, 44, and 45, we did not detect any periodic signals resembling the expected transit feature—which would have a depth of approximately 0.043 percent and a duration of about 0.05 in phase.

Acknowledgments

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