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The Search for Possible Orbital Decays of Hot Jupiters with Data from TESS and Foregone

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Abstract: The existence and large number of discoveries of hot Jupiters challenge the traditional core accretion theory, and there are two unproven hypotheses about the formation and development of hot Jupiters. In this paper, we attempt to provide new clues to support the hypotheses by looking for more possible evidence of hot Jupiters undergoing tidal orbital decay. Combining TESS data with previous astronomical observations creates new possibilities for discovering new candidates. The study found 24 hot Jupiters suspected of orbital decay, when eight of them have reached the point where the trends are clear enough and the data rich enough for further study, and compared them with similar findings made by their peers. This could provide direction for future research.

Keywords: component, astronomy, exoplanet, hot Jupiter, orbital decay

1. Introduction

Hot Jupiters have been studied for three decades, and by the end of this work, hundreds of them have been detected and catalogued in the NASA Exoplanet Archive [1]. But mysterious hot Jupiters still leave a lot of unanswered questions, like how did they form? How did they get to their current orbit? Their future is uncertain [2,3]. One hypothesis posits that exoplanets categorized as hot Jupiters may undergo variations in their orbital periods [4-7]. The factors contributing to potential alterations in the orbital periods of hot Jupiters are multifaceted and intricate. Among the myriads of compelling factors, orbital decay stands out as a particularly competitive mechanism that may account for the observed variations in the orbital periods of hot Jupiters. The phenomenon of orbital decay in the exoplanet WASP-12 b is amenable to direct observational detection [3]. In the realm of exoplanet research, a selection of hot Jupiters stands out as promising subjects for the investigation of orbital decay and the validation of tidal interaction hypotheses, although the variations in orbital periods observed among them, with the exception of WASP-12 b, do not exhibit the same level of persuasion. It is acknowledged that considerable effort is required to discern alterations in orbital periods. Fortunately, the Transiting Exoplanet Survey Satellite (TESS), launched on the 18th of April, 2018, is equipped with an array of identical, highly refined, wide-field cameras designed to survey a 24-degree by 90-degree swath of the celestial sphere [8]. It provides new high-precision 2-minute cadence transit data for the study of the orbital decay of hot Jupiters and extends the observation time baseline, making it possible to search for more direct evidence of the orbital decay of hot Jupiters on this new basis, combining the transit data from TESS with archival data from previous works, such as NASA's *Kepler* mission. new constraints can be placed on the rate of change of the orbital period

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of these hot Jupiters and the tidal dissipation factor of their host stars [9]. Detecting changes in orbital periods requires considerable research and analysis.

In this study, the pursued objective is to identify additional potential hot Jupiters that may exhibit orbital decay and to explore the factors associated with them, as well as to assess their conformity with the simple tidal decay model. Due to the limitations of our capabilities, the investigation from orbital period variations to tidal interactions is not exhaustive. This paper is organized as follows. Section 2 will elucidate the criteria, rationale, and data sources for the selection of the hot Jupiters analysed in this study. Section 3 will delineate the data processing approach of this work, along with its theoretical underpinnings. Section 4 will present the findings of this research, identifying several hot Jupiters with notably decaying orbits and a number of candidates that merit further investigation. It has observed that previous researchers have made discoveries regarding the majority of these planetary systems, albeit with distinct sources of data. The overlap in findings implies a corroboration through cross -validation [9]. Section 5 will delineate the aspects of this study that warrant further investigation. Section 6 provides a summary of this work and an outlook on the future directions of this field.

2. Target selection

In this research, the tidal decay model employed is a straightforward and conventional model of tidal interaction [7]. In this model, the equilibrium tidal bulge is tilted away from the line joining the planet and star by a small and constant angle, and here is its expression about the rate of change of the orbital period $\frac{dP}{dt}$, with the ratio of semi-major axis to stellar radius $\frac{R_*}{a}$, ratio of planetary mass to stellar mass$\frac{M_p}{M_*}$ and the reduced tidal quality factor Q'_*, a dimensionless number16 quantifying the stellar tidal dissipation rate:

$$\frac{dP}{dt} = -\frac{27\pi}{2Q'_*}\left(\frac{M_p}{M_*}\right)\left(\frac{R_*}{a}\right)^5$$

The precondition of expression is that a positively circular planetary system has negligible effects on the angular velocity of the host star and the attenuation of the tides inside the planet. It can be obtained by applying Kepler's third law to Equation (20) of Goldreich & Soter (1966) or Equation (12) of Ogilvie (2014) [7,10,11]. The selection of research subjects primarily adheres to the recommendations outlined in the literature by Patra et al 2020 [7]. However, several key research objects in this paper have not been achieved. Given that the model used is highly sensitive to the ratio of semi-major axis to the stellar radius, and the orbital decay of hot Jupiters is often a prolonged process that occurs on astrophysical relevant timescales, the following analysis was conducted on the data of all eligible confirmed planets in NASA's Exoplanet Archive [1], as of 07/12/2024, that were discovered prior to 2018 for baselines of observation time long enough to yield significant results. In addition, these planets exhibit a ratio of Semi-Major Axis to Stellar Radius less than 10 for an order of magnitude large enough rate of change of the orbital period and a Planet-to-Stellar Radius ratio greater than 0.09 for clear transits not drowned out by noise. We hope that objects with parameters close to WASP-12b will replicate the success of WASP-12b. Hundreds of hot Jupiters fitting these conditions have been analysed in this work, and 24 of them have shown orbital decay trends that may be explained by tidal decay, which would be listed in Section 4.

3. Timing analysis

Research on the tidal-driven hypothesis regarding the origin of hot Jupiters has revealed that many known hot Jupiters are unstable in the face of tidal orbital decay. The sole hot Jupiter directly observed to experience orbital decay is WASP-12, with over a decade of transit timing measurements indicating that its orbital period is diminishing at a rate of approximately dP/dt = 10^{-9} [3,7]. Building on this, the present study employs the following two formulas to analyse the previously selected targets, obtaining data from the lightkurve package to attempt a fit to their light curves and calculate the rate of change of the orbital period, dP/dt. The findings suggest that hot Jupiters exhibiting signs of potential tidal decay typically have a period derivative in the range of 10^{-10} to 10^{-9}, which aligns with the typical upper limits of dP/dt as reported by Patra et al. (2020) [7], being 10^{-9} or 10^{-10}.

$$t_{tra1}(E) = t_0 + PE$$

For planet's Orbital Period as constant.

$$t_{tra2}(E) = t_0 + PE + \frac{1}{2} P \frac{dP}{dt} E^2$$

For Period has a constant derivative with respect to time.

So that we can get the dP/dt by rearranging the equations.

The majority of the subjects investigated in this paper possess a low or null eccentricity, hence this study adopts an approximate circular orbit transit model for the exoplanets [12]. Given that the ratio of planetary radius to the stellar radius for hot Jupiters is typically large and they are in close proximity to their host stars, the brightness of the host stars should not be considered uniform. Instead, it is treated using mandelagol model to more accurately reflect the actual conditions, which uses exact analytic formulae for the eclipse of a star described by quadratic or nonlinear limb darkening, and the accuracy of these formulae are meaningful for planetary systems where the Planet-to-Stellar Radius ratio greater than 0.1, almost exactly covering the scope of this study [13]. The light curve from multiple observational missions of the same star by the lightkurve package are selected as extensively as possible, excluding only the data when obscured by the Earth, the Moon, or any other celestial body. The study also refers to the most precise data on Transit Midpoint, Orbital Period, and Transit Duration provided by the NASA Exoplanet Archive. Segments of the transit light curve, including the start and end of the transit, are extracted and analysed to determine the Epoch (called Orbit number in figures in this paper), as well as the time of conjunction and its uncertainty, which are more in line with the actual conditions.

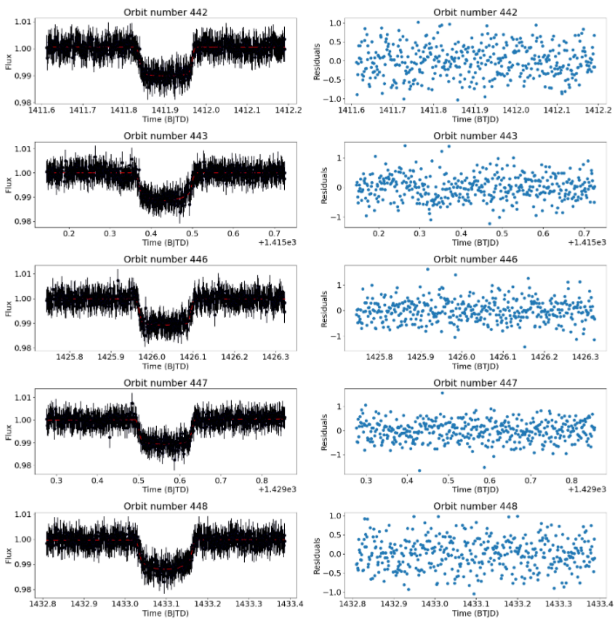

Figure 1: The light curves and residuals of transits

Furthermore, additional timing data from the ephemeris table4 (which are made available online) in Yee et al. (2020) [3] have been fitted in conjunction with lightkurve for comparison, optimizing the fit of the quadratic curve for regression analysis. This process observes whether the predictions for the new TESS data are successful based on previous data. The programming for this aspect builds upon the work of Yee, S. W., Winn, J. N., and others [3].

4. Possible objects of decaying

Upon analysing the data from the two aforementioned sources, a number of hot Jupiters exhibit signs of tidal decay consistent with the model's expectations and credible values of dP/dt in both linear and quadratic fits. It is noteworthy that, due to the limitations of observational time spans and mission accuracy, the light curve data from TESS often are hard to fit a credible quadratic curve on its own. Instead, it should be used more as a supplement and validation to previous observational data. This study categorizes the observed hot Jupiters with relevant signs into three levels based on the degree of orbital decay, and provides a brief introduction to the information and previous research findings of each star. This section will also discuss the anomalies found during the research.

4.1. WASP-12 b

WASP-12 b stands out as the most compelling case of orbital tidal decay observed in hot Jupiters to date [3], thereby serving as a benchmark and reference point for this investigation. Following its discovery in 2008 by Hebb et al. 2009, WASP-12 b has been the subject of intensive and sustained observation by numerous astronomers [14]. According the latest results by Kokori et al. [15], WASP-12 b is a hot Jupiter with 1.937R_J, 1.465M_J, 1.09 days orbit period and the eccentricity was 0.05 [16], rounding with WASP-12, a star of 1.75 R_{sun} and 6154K [1]. Due to it has a temperature over 6000K, the star is considered a hot host star, which may result in weaker tidal interactions in this planetary system (the distinction is related to the inter structure of the star) [7]. The estimated history of the periodic variation of WASP-12 b is as follows: Maciejewski et al. in 2016 first found the change of orbit period of WASP-12 b [9]. Period changes were subsequently confirmed and were explained as a result of orbital decay [3]. In 2022, dP/dt = −29.81 ± 0.94 ms yr^{-1} by Wong, I., Shporer, A., Vissapragada, S., et al. 2022, dP/dt = −29.1 ± 1.0 ms yr^{-1} by Hagey et al., and in 2024, dP/dt = -30.19 ± 0.92 ms yr^{-1} [9]. In this work, dP/dt = -29.69 ± 1.06 ms yr^{-1}. Figure 2 shows its unmistakable conic curve, showing the long-term trend of its continued decay. The dP/dt changes were always within the margin of error, that is, within the margin of error, which is typical of WASP-12b as an example of an orbital tidal decay model.

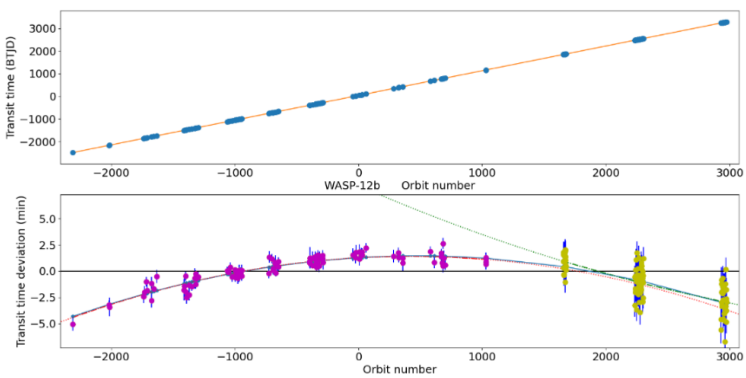

Figure 2: Transit time chart and transit time deviation chart (compared to fixed period model) of WASP-12 b

In Fig.2 Above is the transit time vs epoch and its linear fit line, and below is the transit time deviation vs epoch and its quadratic fit curve of WASP-12 b. The red curve shows the conic fitted by the pre-TESS data and its extension, with magenta data points, the green curve shows the conic fitted by the TESS data and its extension (as you can see, the fit is far from the truth, TESS data are generally not enough to fit a convincing conic on its own) with yellow data points. And the blue curve is the conic fitted by all the data, passing through almost all the data points. As you can see too, the blue and red conics in the figure almost coincide, and the yellow data points falling on the red curve means that the regression analysis is successful, the pre and post observation data are consistent, and the long-term trend is very clear.

By the way, all figures below follow the same laws of color and curve.

4.2. WASP-22 b

This planet has a 1.199 R_J and 0.617 M_J, rounding with a host star with a 1.25 R_{sun}, 1.25 M_{sun} and 6153K effective temperature (a hot host star when the dividing line is 6000K). The long-term TTV trends of WASP-22b seem to be lacking in previous studies, and only one paper has been found to measure its dP/dt, which is -71.76 ± 17.12 ms yr^{-1} [9]. However, in this study, the transit period change of WASP-22b presents an almost perfect conic curve in Figure 3, and the obtained dP/dt = -87.06 ± 23.29 ms yr^{-1} is within the allowable error range of the former, and the value is large and easy to observe. Therefore, it is classified with WASP-12b, and its research prospect is quite worth looking forward to.

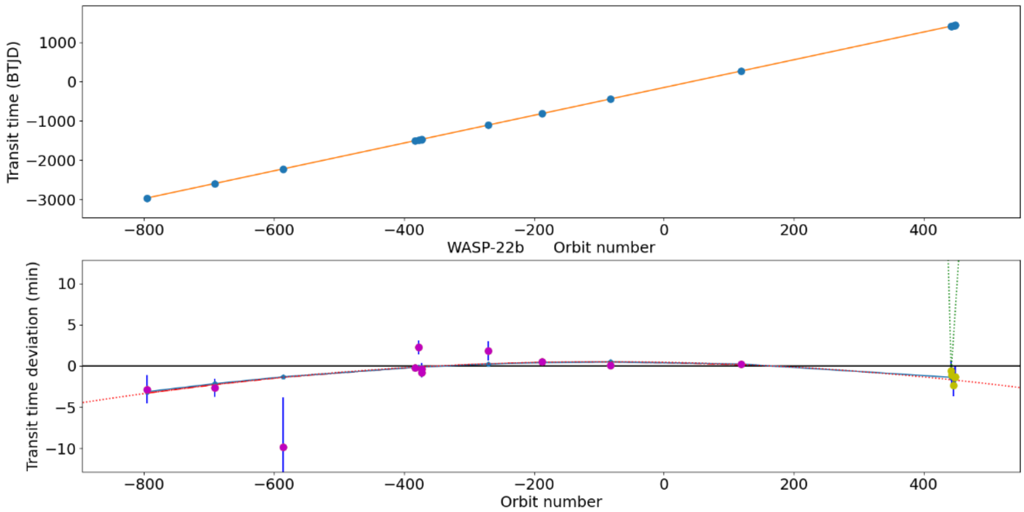

Figure 3: The blue quadratic fit curve of WASP-22 b passes through almost all the data points, with a 16.04 min χ^2 and 13 DOF, which means a 0.247 confidence probability. And it's pretty close to the red curve, which correctly predicted the location of TESS data points in yellow

4.2.1. CoRoT-2 b

CoRoT-2 b was discovered by Alonso et al. (2008), and has a mass of 3.3 M_J and a radius of 1.5 R_J, rounding with a G7V star with a period of 1.743 days. Ivshina & Winn (2022) found the dP/dt = -103.76 ± 6.33 ms yr^{-1} in 2022 [17], but it was fitted to - 21.65 ± 2.96 ms yr^{-1} using the 5σ rejection scheme and −19.12 ± 2.90 ms yr^{-1} using the 3σ rejection scheme by Wang et al [9]. In this work it

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was -55.64 ± 21.59 ms yr^{-1}, it's on the same order of magnitude as the previous data, but unfortunately, it's a big difference.

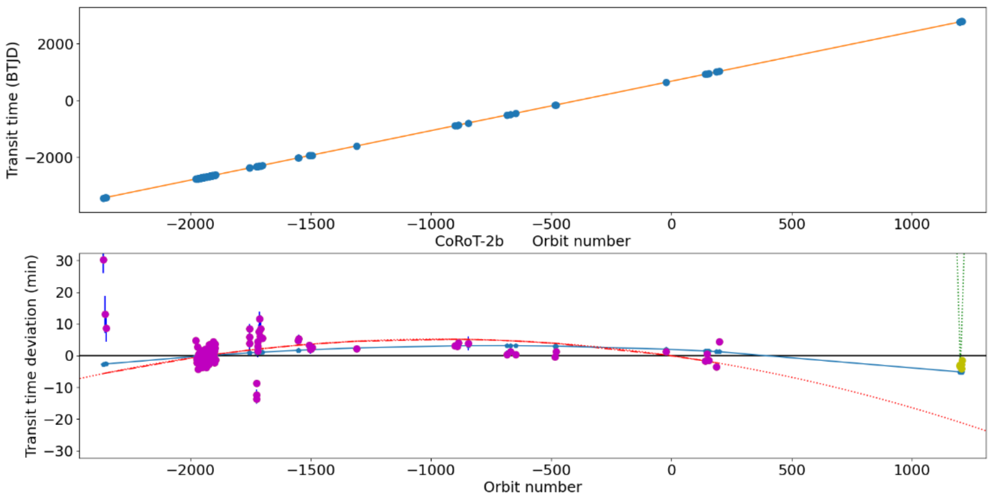

Figure 4: The result of CoRoT-2 b, a mediocre candidate

4.2.2. WASP-4 b

This hot Jupiter showed signs of orbital decay and was well studied since 2019 in Bouma et al. (2019), and has rich results of dP/dt. The Table 1 shows the seven previous results and the result in this work. The table shows that the planet's ratio of the change of orbit period appears to be unstable, at least not as stable as WASP-12 b. But the new data supplied by TESS successfully falls on an extension of the conic fitted to the previous data (See figure 4)

Table 1: dP/dt of WASP-4 b

dP/dt(ms/yr)	-12.6 ± 1.2	-9.2 ± 1.1	-5.94±0.39	-7.33±0.71	-4.8±1.4	-5.81±1.58	-6.43 ±0.55	-7.68±0.89
refences	Bouma et al. (2019)	Southworth et al. (2019)	Baluev et al. (2020)	Turner et al. (2022)	Maciejewski et al. (2022)	Ivshina & Winn (2022)	Wang et al (2024)	This work

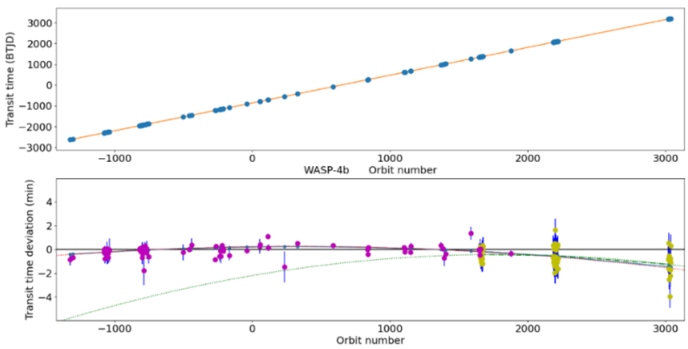

Figure 5: The blue and red curves of WASP-4 b are still very similar and have clear common downward trends. The red curve correctly predicted the location of TESS data points in yellow

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4.2.3. WASP-5 b

WSP-5 b is a hot Jupiter with $1.087R_J$ discovered in 2008. In this work it shows a downward trend with dP/dt = -7.96 ± 3.22 ms yr^{-1}. It seems that no one studied its TTVs before.

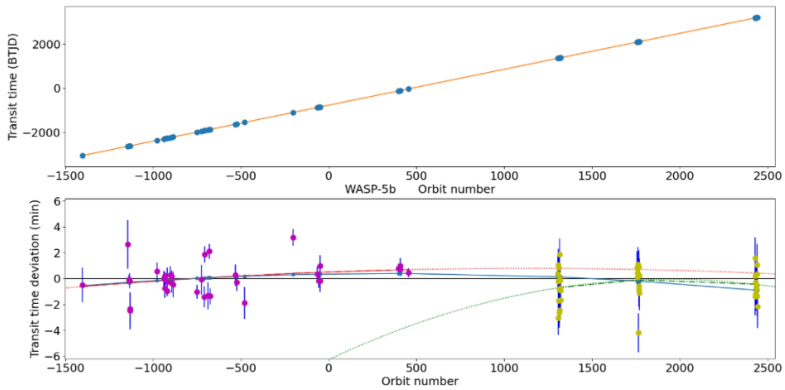

Figure 6: WASP-5 b, with a 125.5 min χ^2 and 72 DOF, which means a 9.64e-05 confidence probability

4.2.4. WASP-10 b

WASP-10 b has been found in 2009 and has a 1.08 R_J when its host star has a 0.70 R_{sun} and 4675K effective temperature. This planet has been study for TTVs, the cause of TTV is varied and conclusive evidence is lacking. In this work, we analysis its TTVs by orbit decay model and calculate the dP/dt = -27.78 ± 6.13 ms yr^{-1}, while Wang et al got dP/dt = -27.74 ± 3.49 ms yr^{-1} in 2024, and it also is consistent with the result from Hagey et al. (2022) [9]. The results are strikingly similar.

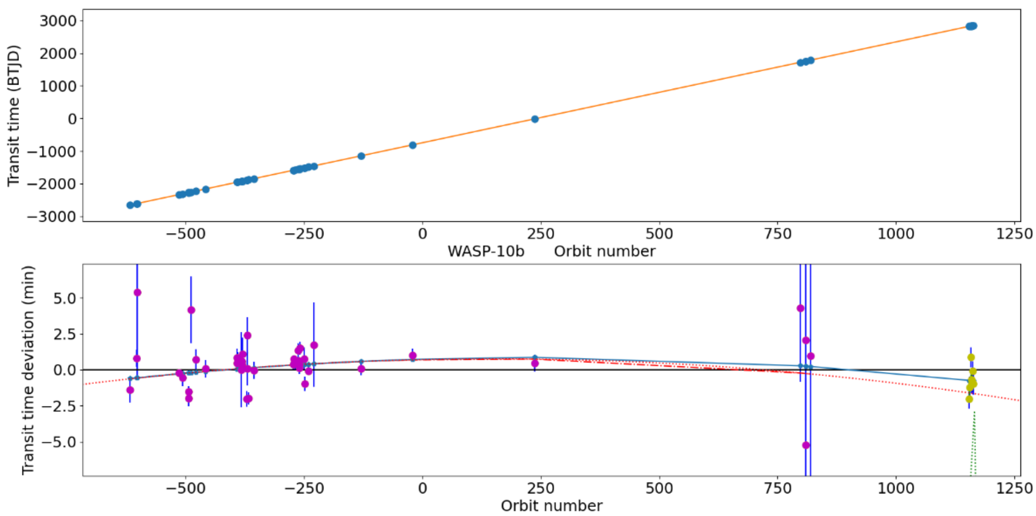

Figure 7: The yellow data points from TESS successfully land on the red pre-TESS data fit curve, with a 122.18 min χ^2 and 46 DOF, which means a 7.90e-09 confidence probability. More TESS data and other data are expected for verify its downward trend

4.2.5. WASP-37 b

It's also a hot Jupiter whose orbital period changes had not been noted before, has a dP/dt = -134.85 ± 50.97ms/yr in this work.

4.2.6. WASP-142 b

It's in a similar situation. dP/dt = -128.86 ± 42.49ms/yr in this work.

4.3. Other candidates

In this research, we have identified several hot Jupiter exoplanets that exhibit a relatively minor orbital decay with low confidence probabilities, indicating the necessity for further observations and analysis to gain a deeper understanding of their dynamical properties and underlying physical processes.

These hot Jupiters include XO-6 b; TrES-3 b; OGLE-TR-113 b; TrES-5 b; WASP-19 b; HAT-P-37 b; TrES-2 b; HAT-P-27 b; WASP-28 b; WASP-16 b; WASP-32 b; KELT-16 b; Qatar-5 b; XO-2 N b; HAT-P-31 b and WASP-167 b.

4.4. Abnormal phenomenon

At the same time, some hot Jupiter orbital periods are seem to actually increase. This is consistent with Wang's findings [9], such as WSAP-17 b. Which has a result dP/dt = 98.34 ± 39.06 ms yr^{-1} in this work, and is consistent with the result from Wang et al 's dP/dt = 77.64 ± 8.19 ms yr^{-1}, but they have a very different optimization result dP/dt = 3.36 ± 4.46 ms yr^{-1} [9].

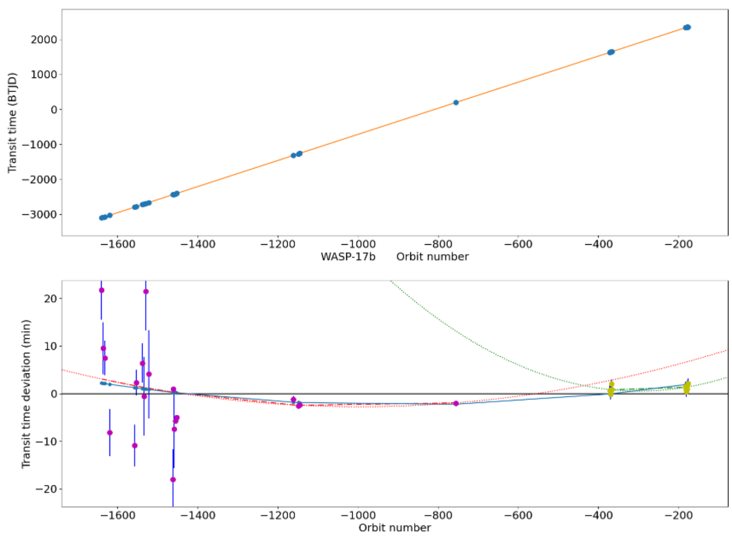

Figure 8: Anomalous WASP-17 b image

5. Arrear

Due to the limitation of academic level and research cycle, this paper has not fully investigated the cases found, so the results can only be called "suspected". There is a long way to go from transit time deviation to tidal attenuation. The following effects and possibilities were not considered in this study:

1. Rømer effect, which maybe need to analysis more radial-velocity data to identify whether it's Rømer effect or tidal decay resulting in orbital period decay.

2. Apsidal precession. Due to using simple right circle transit model to analysis planets' light curve data, any possible effects of orbit eccentricity and precession are not discussed in this paper, and further optimization of the model is needed to make the results more realistic.

3. Other planets. Some of orbital period decay should be attributed to perturbations from other potential planets, such as WASP-4 b was suspected to be influenced by WASP-4 c. Turner et al. (2022)

4. Tidal demise or mass decay. Hot Jupiters are so close to their host stars, so it is both possible that their masses are gradually lost due to solar activity or that they undergo tidal extinction. Future studies should emphasize the dynamic nature of hot Jupiter planetary systems

5. General relativity. All the analyses in this paper are confined to classical mechanics and the relativistic effects are ignored.

6. Conclusion

In this paper, some possible hot Jupiters undergoing orbital decay are pointed out, their properties are briefly analysed, and their research history is reviewed. But without enough data to support them, it can be said that several candidates are suggested for future research.

The most successful example of tidal decay on a hot Jupiter, WASP-12 b, has been observed for more than 5,000 orbital periods with really high data quality. High enough data quality and long enough measurement time spans are generally lacking for the remaining planets in this study. And these have become important constraints to the results of this study. In addition, the optimization of models and algorithms needs to continue and continue. However, extending the observation time baseline is still the best partner for finding evidence of orbital decay of hot Jupiters. As the baseline longer, longer and longer, more and more candidates continue to emerge. With further extension of the time baseline, it will become easier to find cases of orbital decay of hot Jupiters in subsequent studies, and it is believed that the tidal interaction model will be perfected in a few years, and the two hypotheses about hot Jupiters will be clarified. The future is bright.

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