Revisiting BD–06 1339b: A Likely False Positive Caused by Stellar Activity

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Abstract

As long as astronomers have searched for exoplanets, the intrinsic variability of host stars has interfered with the ability to reliably detect and confirm exoplanets. One particular source of false positives is the presence of stellar magnetic or chromospheric activity that can mimic the radial velocity reflex motion of a planet. Here we present the results of a photometric data analysis for the known planet-hosting star BD –06°1339, observed by the Transiting Exoplanet Survey Satellite during Sector 6 at a cadence of 2 minutes. We discuss evidence that suggests that the observed 3.9-day periodic radial velocity signature may be caused by stellar activity rather than a planetary companion, since variability detected in the photometric data is consistent with the periodic signal. We conclude that the previously reported planetary signature is likely the result of a false-positive signal resulting from stellar activity, and we discuss the need for more data to confirm this conclusion.

Unified Astronomy Thesaurus concepts: Exoplanet detection methods (489); Exoplanet astronomy (486); Stellar activity (1580); Stellar photometry (1620); Stellar rotation (1629); Radial velocity (1332); Exoplanets (498)

1. Introduction

Exoplanet discoveries thus far have been dominated by indirect techniques, mostly due to the success of the radial velocity (RV) and transit techniques. Prior to the discoveries of the Kepler mission (Borucki et al. 2010; Borucki 2016), the majority of exoplanets were discovered using the RV method (Butler et al. 2006; Schneider et al. 2011), with a growing number of ground-based transit discoveries (Konacki et al. 2003; Alonso et al. 2004; Bakos et al. 2007; Kane et al. 2008). Indirect detection techniques rely on a detailed characterization of the host star, since the properties of the host star determine the extracted planetary parameters (Seager & Mallén-Ornelas 2003; van Belle & von Braun 2009). Of particular importance is the effect of stellar activity, since this can severely limit the detection of exoplanets around active stars (Desort et al. 2007; Aigrain et al. 2012; Zellem et al. 2017) and can even result in false-positive detections, whereby stellar activity cycles can masquerade as exoplanet signatures (Nava et al. 2020). Indeed, there have been numerous instances of exoplanet claims using the RV method that were later determined to be the result of stellar activity (Henry et al. 2002; Robertson & Mahadevan 2014; Robertson et al. 2015; Kane et al. 2016). This potential confusion may be mitigated in certain cases by utilizing precision photometry for known exoplanet hosts (Kane et al. 2009), such as data acquired by transit surveys. A transit detection of an RV planet can provide confirmation of the planet, as well as provide an additional means to disentangle stellar variability and planetary signatures (Boisse et al. 2011; Díaz et al. 2018). The Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) provides an invaluable photometric data source for known exoplanet hosts (Kane et al. 2021), since it is monitoring most of the sky, and is especially well suited for observing the bright host stars typical of RV exoplanet searches (Fischer et al. 2016).

Stellar activity has long been known to affect and sometimes limit RV exoplanet searches (Saar & Donahue 1997) and can particularly impact detection of planets within the habitable zone (Vanderburg et al. 2016). Photometric monitoring of known host stars has been used in numerous cases to determine the effects of their variability on planetary signatures, such as for HD 63454 (Kane et al. 2011) and HD 192263 (Dragomir et al. 2012). Another example of a host star exhibiting significant stellar variability is the case of BD –06°1339, which was discovered to host planets by Lo Curto et al. (2013) using data from the High Accuracy Radial velocity Planet Searcher (HARPS) spectrograph (Pepe et al. 2000). These observations revealed two planetary signatures with orbital periods of 3.87 and 125.94 days, with minimum planetary masses of 0.027 and 0.17 MJ, respectively. However, photometry of sufficient precision, cadence, and duration was not available in order to confirm a transit signature.

Here we present an investigation into the BD–06 1339b planetary signature by analyzing the associated TESS photometry and reanalyzing the existing HARPS RV data. In Section 2, we discuss the properties of the system, including the stellar parameters, and the possible planets within the system. Section 3 describes the data analysis for the system, where the data sources are composed of HARPS RV data and the precision photometry from TESS. Section 4 combines these results to present an argument that the RV variations originally detected could alternatively be consistent with the intrinsic variability of the host star. We provide concluding remarks in Section 5 and outline how the photometric capabilities from TESS not only serve to discover new planets but also have considerable utility in testing known exoplanet hypotheses.

2. System Properties

BD –06°1339 (HIP 27803, GJ 221, TIC 66914642) is a relatively bright high-proper-motion star located at a distance...
of 20.27 pc (Gaia Collaboration et al. 2018, 2021). According to Lo Curto et al. (2013), BD −06°1339 is a late-type dwarf star, with a spectral classification of K7V/M0V and an age similar to that of the Sun. The star has an effective temperature of 4324 K, a V magnitude of 9.70, and a stellar mass of 0.7 \( M_\odot \).

Initial spectroscopic analyses were performed in 1996 for the Palomar/MSU Nearby Star Spectroscopic Survey (Hawley et al. 1996) among previously reported variable stars. A further survey of chromospheric activity among cool stars by Boro Saikia et al. 1996 among active, with an activity index of \( \log R_{HK} = -4.71 \). Such magnetic activity is prevalent in later stellar spectral types (McQuillan et al. 2012), lending to the stellar activity of interest for this study.

The host star is currently reported to have two companions, BD-06 1339b and BD −06°1339c, both of planetary mass and discovered via the RV technique (Lo Curto et al. 2013). Though discovered simultaneously, their properties differ greatly; BD-06 1339b has a minimum mass of 8.5 \( M_\oplus \) and orbits its host star in 3.873 days at a semimajor axis of 0.0428 au. Its sibling, BD −06°1339c, has a minimum mass of 53 \( M_\oplus \) and an orbital period of 125.94 days at a semimajor axis of 0.435 au. The Lo Curto et al. (2013) analysis of the RV data for BD-06 1339b adopts a fixed circular orbit (\( e = 0 \)) for the b planet and derives an eccentricity of 0.31 for the c planet. Tuomi (2014) conducted a statistical reanalysis of the RVs for BD −06°1339, which we further investigate in Section 3.1.

3. Data Analysis

The motivation for reanalyzing BD-06 1339b stems from a broad stellar variability analysis of stars observed during the TESS primary mission at a cadence of 2 minutes (Fetherolf et al. 2022, in preparation) and a further investigation into the stellar variability of known exoplanet host stars (Simpson et al. 2022, in preparation). The broad stellar variability analysis by Fetherolf et al. (2022, in preparation) searches for periodic photometric modulations on timescales up to the duration of a single orbit of the TESS spacecraft (0.01–13 days), during which TESS obtained continuous observations. The \( \sim \) 700 exoplanet host stars that were selected for the follow-up variability analysis by Simpson et al. (2022, in preparation) include planets with orbital periods shorter than 13 days that were discovered by either their RV or transit signatures. Since Kepler exoplanet host stars are typically faint and not ideal for RV follow-up observations, they are not included in the stellar variability analysis of known exoplanet host stars. In addition to possible transit events or variations due to stellar activity, some of these planets may also exhibit interactions with their host stars, such as phase variations or star-surface irregularities.

The full TESS light curve, Lomb–Scargle (L–S) periodogram, and light curve that was phase-folded on the most significant photometric variability signature were each visually inspected for the \( \sim 700 \) known exoplanet host stars. The photometric periodicity was determined to be significantly variable if both the normalized and phase-folded light curves displayed sinusoidal behavior that did not align with known spacecraft systematics (i.e., momentum dumps) and if the periodogram maximum exhibited an isolated peak with at least 0.001 normalized power that also exceeded the 0.01 false-alarm probability level. For each known exoplanet, the extracted photometric variability period was compared to their orbital period, as reported either by the TESS Objects of Interest catalog (Guerrero et al. 2021) or by cross-referencing the target in the NASA Exoplanet Archive (NASA Exoplanet Archive 2021). Close-period matches between the photometric variability and the planetary orbital period were defined as being within 5%–10% of each other. Out of the \( \sim 700 \) targets subjected to the visual analysis, approximately 180 systems displayed prominent photometric variable behavior, close-period matches, or both.

BD-06 1339b was among the set of targets that matched these criteria, and the resulting TESS light curve, periodogram, and phase-folded light curve are shown in Figure 1 (see also Section 3.2). In this paper we revisit the analysis of the BD −06°1339 system by including the TESS photometry that was unavailable at the time of previous studies. In Section 3.1 we summarize our reanalysis of the RVs using the data provided by the updated HARPS reduction pipeline (Trifonov et al. 2020). We then discuss our in-depth analysis of the TESS photometry in Section 3.2, where we search for the presence of planetary transits, atmospheric variations, and stellar activity.

3.1. Spectroscopic Analysis

Lo Curto et al. (2013) verified the planets orbiting BD −06°1339 by requiring the normalized Fourier power of the L–S periodogram of the RV time series to have a false-alarm
probability of $<10^{-4}$. The log $R'_{HK}$ activity index was considered poor quality and therefore was not utilized in the overall analysis. BD-06 1339b was barely discernible within the RV signal of BD $-06\ddgree 1339c$ in this stage of analysis, existing initially as additional variations. To verify the planetary nature of this signal, the founding team cut the data sets in half to exclude long-term trends. These variations then increased in strength throughout the observation period as the Ca II H reemission decreased. The discovery team was unable to determine any other longer-term trends owing to their limited window of 102 observations over 8 yr. They determined that BD-06 1339b was an educational case of how planets can hide within the activity of variable stars.

To further analyze the BD $-06\ddgree 1339$ system, Tuomi (2014) implemented a more meticulous probability check involving an independent statistical method of subsequent samplings and the utilization of log-Bayesian evidence ratios. The Bayesian analysis used by Tuomi (2014) evaluated the RV time series as if they were observed in real time. At each iteration, a “new” RV measurement was added to the data set from which the best-fit system parameters were determined. In this case, they utilized HARPS and Planet Finder Spectrograph (PFS; Crane et al. 2010) velocities in their credibility tests. HARPS found the planetary signals of the two original targets, which were consistent with each other. PFS could not discern any signals previously found by Lo Curto et al. (2013). The system itself was not explicitly observed for this publication, instead relying on the previous data available at the time. Their results focused on the discovery of a third d planet at a $\sim$400-day orbital period based on a statistical probability, and they considered BD-06 1339b as a confirmed planet.

The observations of BD $-06\ddgree 1339$ were acquired by the HARPS team and originally published by Lo Curto et al. (2013). The data have since been re-reduced and include corrections of several systematics within the observations (Trifonov et al. 2020). With the improved precision and availability of the data, a reanalysis could derive the orbital parameters of the known companions in the system with better precision and potentially reveal smaller signals that were previously unreported before the reeducation of the RVs.

We performed a reanalysis of the RVs for BD $-06\ddgree 1339$ using the re-reduced data published by Trifonov et al. (2020). We first ran an RV Keplerian periodogram on the data set to search for significant signals using RVSearch (Rosenthal et al. 2021). The RVSearch algorithm iteratively searches for periodic signals present in the data set and calculates the change in the Bayesian information criterion ($\Delta BIC$) between the model at the current grid and the best-fit model based on the goodness of the fit. The result of the search would yield signals that are of planetary origin, as well as those that are due to stellar activity. We adopted signals returned by RVSearch if they peak above the 0.1% false-alarm probability level. The search returned two significant signals, one at 125 days and another at 3.9 days. This is consistent with the results from Lo Curto et al. (2013).

We then used the RV modeling toolkit RadVel (Fulton et al. 2018) to fully explore the orbital parameters of these two signals and to assess their associated uncertainties. We provided the orbital parameter initial guesses for the two signals using the values returned by RVSearch and allowed all parameters to vary, including an RV vertical offset, RV jitter, and a linear trend. We fit the data with maximum a posteriori estimation and explored the posteriors of the parameters through Markov Chain Monte Carlo (MCMC). The MCMC exploration successfully converged, and we show the results in Table 1.

Orbital parameters of the two signals are mostly consistent with those reported by Lo Curto et al. (2013), except that the orbit of the c planet is preferred to be nearly circular ($e_c \sim 0.09$) instead of mildly eccentric ($e_c \sim 0.31$), as proposed by Lo Curto et al. (2013). In addition, there appears to be a significant linear trend ($\sim 7\sigma$) present in the data that could be indicative of an additional long orbital period, massive companion orbiting in the outer regime of this system. Both the linear trend and two-circular-orbits model are supported by Bayesian model comparisons. The RV signature for BD-06 1339b is shown in the left panel of Figure 2, where the contribution from the c planet has been removed. The results of this latest RV reanalysis are consistent within the uncertainties of the original analysis performed by Lo Curto et al. (2013).

### 3.2. Photometric Analysis

Gillon et al. (2017) used the Warm mode of the Spitzer mission to search for transits of 24 low-mass planets (all single-planet systems) discovered through the RV method, including BD-06 1339b. The Spitzer photometry found no reliable transits for 19 of the 24 planets, including BD-06 1339b. Specifically, BD-06 1339b was found to not display a transit within the observation window, although the photometry did not cover approximately 20% of the possible transit window. Since then, TESS observed BD $-06\ddgree 1339$ at a cadence of 2 minutes nearly continuously during the observations of Sector 6. In this section, we use the TESS photometry to search for transits by either the b planet or the c planet and atmospheric phase variations caused by the b planet.

BD $-06\ddgree 1339$ was observed during TESS Sector 6 (2018 December 11–2019 January 07) at a cadence of 2 minutes and TESS Sector 33 (2020 December 17–2021 January 13) at a cadence of 30 minutes. The TESS light curves and full-frame images are publicly available through the Mikulski Archive for Space Telescopes (MAST). Since the anticipated transit of BD-06 1339b is on the order of $\sim 2$ hr, we elect to only use the 2-minute-cadence light curve from the Sector 6 observations. We use the original data release of the pre-search data conditioning (PDC) light curve that was processed by the

### Table 1

| Parameters | b | c |
|------------|---|---|
| $P$ (days) | 3.87302$^{+0.00035}_{-0.00031}$ | 125.49 $^{+0.13}_{-0.13}$ |
| $T_c$ (BJD) | 2455000.91$^{+0.01}_{-0.01}$ | 2455279.6$^{+2.0}_{-1.8}$ |
| $T_p$ (BJD) | 2455001.65$^{+0.039}_{-0.062}$ | 2455285.16$^{+16}_{-14}$ |
| $e$ | 0.22$^{+0.16}_{-0.13}$ | 0.089$^{+0.054}_{-0.052}$ |
| $\omega$ (deg) | 181.23$^{+58.39}_{-35.00}$ | 110.58$^{+38.39}_{-29.27}$ |
| $K$ (m s$^{-1}$) | 3.47$^{+0.52}_{-0.49}$ | 8.32$^{+0.6}_{-0.47}$ |
| $M_p$ (M$_\odot$) | 6.45$^{+0.98}_{-1.16}$ | 50.9$^{+4.4}_{-4.3}$ |
| $a$ (au) | 0.0429$^{+0.0014}_{-0.0015}$ | 0.436$^{+0.014}_{-0.015}$ |

Note. $\omega$ values are those of the star, not of the planet. The RV fit includes a linear trend of $\gamma = -0.00239^{+0.00035}_{-0.00033}$ m s$^{-1}$ day$^{-1}$. 

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5 https://archive.stsci.edu/
Science Processing Operations Center (SPOC) pipeline (Jenkins et al. 2016) and additionally remove any observations denoted with poor-quality flags or that are 5σ outliers. The L–S periodogram (Lomb 1976; Scargle 1982) is then computed on the BD $-06^\circ 1339$ light curve using an even frequency spacing of 1.35 minute$^{-1}$, where we find a maximum normalized power of $\sim 0.0038$ at $3.859 \pm 0.325$ days. The 0.01 false-alarm probability level for the periodogram of the BD $-06^\circ 1339$ light curve corresponds to 0.0012 normalized power, with the peak of the periodogram having a $\leq 10^{-4}$ false-alarm probability.

Our L–S periodogram analysis of the TESS light curve reveals a sinusoidal periodicity that is consistent with the orbital period of the b planet (3.8728 $\pm$ 0.0004 days) within their uncertainties (see Figure 1). A planet’s orbital period may be extracted from a periodogram analysis if transit events are not properly removed from the observed light curve. However, we do not observe transit events by either the b planet or the c planet in the TESS photometry (see Figure 2), which is consistent with the findings of Gillon et al. (2017). A significant sinusoidal amplitude could also indicate the presence of a planet-induced photometric phase curve caused by its dayside reflection or excess thermal emission. If the phase curve is caused by the dayside reflection of the planet, then the maximum brightness of the phase-folded light curve is expected to peak at 0.5 phase when we see the greatest area of the planet illuminated from our point of view. Alternatively, atmospheric winds that redistribute heat from the dayside to nightside could cause the hottest region of the atmosphere to be shifted eastward from the substellar point, such that the phase-folded light curve peaks prior to 0.5 phase (e.g., Showman et al. 2013; Heng & Showman 2015).

We use the measured time of conjunction (i.e., expected transit time) from the RV analysis to assess both the shape and phase of maximum amplitude of the TESS phase-folded light curve for BD-06 1339b. The full phase curve is fit using a double harmonic sinusoidal function, which allows for modulations caused by Doppler boosting and ellipsoidal variations in addition to the reflection caused by the dayside of the planet (see Shporer 2017). The first cosine harmonic component represents the modulations caused by dayside reflection or thermal emission, such that the maximum brightness occurs at 0.5 phase. The phase-folded light curve of BD-06 1339b exhibits a significant sinusoidal modulation of $\sim 40$ ppm in the TESS photometry (see right panel of Figure 2), with a maximum brightness at the third quadrature of the b planet’s orbital phase (0.73 phase). In addition to the maximum brightness being at a phase that is inconsistent with dayside reflection or thermal emission, the amplitude of the phase curve is $\sim 10$ times greater than expected for such a small planet.6

4. False-positive Planetary Signature?

The results described above cast doubt on the planetary origin of the signal ascribed to BD-06 1339b. This target may, in fact, instead be a possible case for the stellar variability of the host star masquerading as a false positive. While it is not impossible for a system to exist in which a planet orbits at the same period as its host star’s variability, a coincidence of 0.01 days between the two is highly unlikely. A visual comparison of the RVs and stellar flux of the host star is enough to raise some questions, but we must quantify our results. We further investigate the nature of BD-06 1339b by comparing the phase signature in the RVs and photometry, searching for correlations in the spectral activity indicators, and considering the likelihood of BD $-06^\circ 1339$ exhibiting periodic stellar activity at $\sim 3.9$ days.

Figure 2 shows the RV signature and the photometric variations in phase with the anticipated orbit of BD-06 1339b. We fit a simple sinusoidal function to each phase curve and find that the maximum of the RVs occurs at 0.69 phase with an amplitude$^7$ of 3.3 m s$^{-1}$ and the maximum of the photometric flux occurs at 0.73 phase with an amplitude of 40 ppm. Interestingly, the RVs and the photometric variations peak at approximately the same phase. The correlation between these sinusoidal functions is further emphasized in Figure 3, where

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6 The dayside reflection modulations of a 8.5 $M_j\oplus$ planet with an albedo of 0.3 are expected to be on the order of $\sim 2$ ppm.

7 This amplitude is estimated assuming a simple sinusoidal function and thus a zero eccentricity.
the photometric variations should peak at 0.5 phase or earlier and the photometry, but they should instead be offset from each other in phase. If the photometric variations were caused by atmospheric resection or thermal emission of BD–06°1339b, the photometric variations should peak at 0.5 phase or earlier owing to winds (e.g., Showman et al. 2013; Heng & Showman 2015). However, the observed phase offset is subject to uncertainties from the time of conjunction determined from the RVs (0.2 days) and the time between the RV and TESS observations (∼3500 days). Propagating the time of conjunction, and thus phase offset, out to the time of the TESS observations results in an uncertainty of 0.5 days (13% of the orbital period), which could render the correlation in phase between the RVs and photometry as a coincidence.

In addition to the photometry, we performed an analysis on all of the available RV activity spectral indicators provided by the HARPS RV database (Trifonov et al. 2020) to investigate whether any significant activity signals are consistent with the reported period for BD–06°1339b. We used a Generalized L–S periodogram (GLS; Zecheister & Kürster 2009) to search for periodicity in Hα, chromatic index (CRX), differential line width (dLW; Zecheister et al. 2018), and FWHM and contrast of the cross-correlation function (CCF). None of the aforementioned indicators returned significant signals above the 0.1% false-alarm probability level, except for dLW, where a ∼270-day signal was detected just above the false-alarm probability threshold and is possibly of stellar activity origin.

We also investigated whether there exists any correlation between the b planet’s RV signal (after the removal of RV contributions from the c planet and the linear trend) and each one of the activity indicators using the Pearson correlation coefficient. Once again, only dLW returns a weak correlation of ∼0.25, while there is no correlation observed in any of the other activity indicators. While there is no peak in the dLW periodogram near ∼3–4 days, the correlation between the b planet’s RV signature and dLW could be related to the 270-day signal. Overall, despite the strong indication from the photometry that the previously reported b signal could be attributed to stellar activity, no significant correlations were found between the b planet’s RVs and any of the spectral activity indicators, and no activity periods were detected near the b planet’s orbital period.

This raises the question of how stellar variability can be selectively manifesting in the photometry, but not in the spectral lines of the host star. We investigate whether the signal observed in the BD–06°1339 light curve is typical for stars of similar spectral types. From the all-sky variability analysis, we searched for stars with effective temperatures between 4000 and 4500 K, photometric variability periods of 3.5–4.0 days, and stellar luminosities lower than 10 L☉. We find ∼30 stars within this subgroup and, upon visual investigation, find that their light curves are similar in shape and amplitude to the variations observed for BD–06°1339 (see Figure 1). Their light-curve behavior proved to be comparable to what is observed in the BD–06°1339 light curve. Therefore, stellar activity is a potential explanation for the observed photometric variations.

We cannot pinpoint the physical mechanism behind the photometric variability, although our general understanding of stellar astrophysics suggests that it is related to magnetic activity in the star that produces spots and plages. The false-alarm probability (Lo Curto et al. 2013) used to detect BD–06°1339b was based on a simple f-test, but recent work has shown that other statistical methods, such as the extreme value statistical distribution, may be more appropriate for applying to periodogram analyses (Süveges 2014; Vio & Andreani 2016; Sulis et al. 2017; Vio et al. 2019; Delisle et al. 2020). The close match between both the period and phase of the photometric variability and the RV variations suggests that both signals are produced by the same cause. We therefore believe that the most likely explanation is that BD–06°1339b is a false positive and that the RV variations are not produced by a planetary companion of the star.

5. Conclusions

We conducted a photometric analysis of targets with periodic modulations from the TESS primary mission (T. Fetherolf et al. 2022, in preparation; E. Simpson et al. 2022, in preparation) and determined that BD–06°1339b was considered a prime subject for further scrutiny. The similarity between the photometric variability periodicity of the TESS photometry for BD–06°1339 (3.859 days) and the orbital period of the b planet (3.874 days) prompted a rigorous reexamination of the spectroscopy and photometry for this target. We performed a reanalysis of the RVs obtained by HARPS and found an orbital solution that was consistent with the RV analysis performed by Lo Curto et al. (2013). An in-depth investigation of the photometric variations revealed that they were inconsistent with atmospheric phase variations due to the planet based on their phase and amplitude, but they could possibly be attributed to stellar activity. Comparing the RV analysis with the phasefolded photometric fluxes (see Figure 2) revealed a strong correlation between the two data sets (see Figure 3).

With these results in mind, we addressed what this means for the interpretation of the RV modulation observed near 3.9 days, previously attributed to a planetary signal. Stellar activity is a possible culprit, but the spectroscopic emission lines of this star do not correlate well with the photometric modulations of this star. Therefore, there is a wide field of opportunity for this target to be analyzed further to determine the source of the
discrepancy between the photometric and spectroscopic behavior.

These results indicate that BD-06 1339b is, in fact, a likely false positive whose signature was induced by the activity of the star. Follow-up observations could help to resolve the discrepancy between the photometric and spectroscopic data. In particular, understanding the nature of the discrepancy would benefit from additional precision photometry of the star to improve the characterization of the stellar variability, alongside simultaneous spectroscopic activity indicators (Díaz et al. 2018) and an extended RV baseline. Overall, reanalysis of this systems emphasizes the greater importance of further verifying the nature of confirmed RV planets as new data become available—especially for those that are low in mass and of high interest to demographics and atmospheric studies.

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Facilities: TESS, HARPS, NASA Exoplanet Archive.

Software: Astropy (Astropy Collaboration et al. 2013, 2018), Astroquery (Ginsburg et al. 2019), GLS (Zechmeister & Kürster 2009), Lightkurve (Lightkurve Collaboration et al. 2018), RadVel (Fulton et al. 2018), RVSearch (Rosenthal et al. 2021), Matplotlib (Hunter 2007), NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020).

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