Nodal Precession and Tidal Evolution of Two Hot-Jupiters: WASP-33 b and KELT-9 b

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ABSTRACT

Hot Jupiters orbiting rapidly rotating stars on inclined orbits undergo tidally induced nodal precession measurable over several years of observations. The Hot Jupiters WASP-33 b and KELT-9 b are particularly interesting targets as they are among the hottest planets found to date, orbiting relatively massive stars. Here, we analyze archival and new data that span 11 and 5 years for WASP-33 b and KELT-9 b, respectively, in order to to model and improve upon their tidal precession parameters. Our work confirms the nodal precession for WASP-33 b and presents the first clear detection of the precession of KELT-9 b. We determine that WASP-33 and KELT-9 have gravitational quadrupole moments \((6.3^{+1.2}_{-0.8}) \times 10^{-5}\) and \((3.26^{+0.93}_{-0.80}) \times 10^{-4}\), respectively. We estimate the planets' precession periods to be \(1460^{+170}_{-130}\) years and \(890^{+200}_{-140}\) years, respectively, and that they will cease to transit their host stars around the years \(2090^{+17}_{-10}\) CE and \(2074^{+20}_{-10}\) CE, respectively. Additionally, we investigate both planets' tidal and orbital evolution, suggesting that a high-eccentricity tidal migration scenario is possible to produce both system architectures and that they will most likely not be engulfed by their hosts before the end of their main sequence lifetimes.

1. INTRODUCTION

Over recent decades the number of discovered exoplanets has steadily increased into the thousands, revealing a large variety of exoplanet system orbital architectures around stars of any life stage covering a large range of stellar masses and life stages (e.g., Howard et al. 2012; Charpinet et al. 2011; Barnes et al. 2013; Gettel et al. 2012; Nowak et al. 2013; Reffert et al. 2015; Niedzielski et al. 2015, 2016). Of peculiar interest among these exoplanetary systems have been Hot Jupiters (HJs), which orbit their stars with periods of 10 days or shorter, as such planets do not exist in our own solar system. Additionally, many discovered HJs have strong spin-orbit misalignments with their host stars, often even being in retrograde orbits (e.g., Albrecht et al. 2012; Winn & Fabrycky 2015). This, together with planet formation models, supports the idea that HJs are not born at their current orbital configuration, but have migrated post-formation by some dynamical mechanism (e.g., Nagasawa et al. 2008; Naoz et al. 2011, 2013, 2012).

Regardless of the formation or migration mechanisms, spin-orbit misaligned HJs present a unique observational opportunity to measure tidally induced nodal precession of an HJ’s orbit, if the host star is oblate due to rapid rotation. As colder, more convective stars tend to “spin down” rapidly due to magnetic braking as they age (e.g., Kawaler 1988), hotter \((T_{\text{eff}} > 7000 \text{ K})\), stars with radiative envelopes can stay fast-spinning for most of their main-sequence (MS) life time (e.g., Meynet et al. 2011). Therefore, misaligned HJs around hot stars are ideal targets for measuring nodal precession.

Here, we present our observations and analysis of the nodal precession and tidal dynamics of two HJs orbiting two hot, rapidly spinning stars, WASP-33 b and KELT-9 b. These exoplanets are among the hottest exoplanets that have been discovered over recent decades, orbiting stars with effective temperatures above 7400 K.
and 10,000 K, respectively (e.g., Collier Cameron et al. 2010a; Gaudi et al. 2017). Both planets have been extensively studied by previous works, investigating among other factors their orbits and atmospheres (e.g., Collier Cameron et al. 2010a; von Essen et al. 2014; Johnson et al. 2015; Gaudi et al. 2017; Ahlers et al. 2020; Watanabe et al. 2020; Borsa et al. 2021; Pai Asnodkar et al. 2022a,b), and are known to have large spin-orbit misalignments. In this work we obtain new data to extend the timeline of nodal precession measurements by several years for both planets compared to previous works (see Sections 2 and 3.3), allowing us to derive more accurate tidal parameters for both systems (see Section 4). Additionally, we estimate the past tidal evolution of both planets, allowing us to set limits to the formation and migration mechanisms that brought them to their current configurations (see Section 5).

2. OBSERVATIONS

2.1. WASP-33 b

We use archival data for WASP-33 b that were obtained by Harlan J. Smith Telescope (HJST) with Robert G. Tull Coude Spectrograph (Tull et al. 1995) at McDonald Observatory on UT 2008 November 12th (Collier Cameron et al. 2010b) and UT 2014 October 4th (Johnson et al. 2015).

In addition, we include new data from HJST that were obtained on UT 2016 December 11 and data from the PEPSI (Strassmeier et al. 2015) spectrograph on the Large Binocular Telescope (LBT) on UT 2019 November 17 (Cauley et al. 2020).

There are also archival data from the Subaru telescope. However, we do not have access to the Subaru data that were obtained on UT 2011 October 19 (Watanabe et al. 2020). Because the Subaru observation was bracketed by the two ends of the time baseline from 2008 to 2019, the Subaru data are non-essential in the subsequent analyses. For a similar reason, we do not include archival data from HARPS-N that span from 2016 to 2019 (Borsa et al. 2021).

2.2. KELT-9 b

We use archival data in the discovery paper (Gaudi et al. 2017). These data were obtained by the Tillinghast Reflector Echelle Spectrograph (TRES) on the 1.5 m telescope at the Fred Lawrence Whipple Observatory on UT 2014 November 14, 2015 November 06, and 2016 June 12.

We also include archival data that were obtained since the discovery. The data include two transits observed with the HARPS-N spectrograph mounted on the Telescopio Nazionale Galileo (TNG) in La Palma, Spain on UT 2017 Aug 01 and 2018 Jul 21 (Hoeijmakers et al. 2019), and one transit observed with PEPSI at LBT on UT 2018 Jul 03 (Cauley et al. 2019).

In addition, we add a new data set from PEPSI at LBT that were observed on UT 2019 Jun 22, therefore extending the time baseline to ~5 years from 2014 to 2019. We note that CARMENES (Quirrenbach et al. 2018) has also observed KELT-9 b (Yan et al. 2019). The observation was made on UT 2017 Jan 5. We do not include this data point because it falls in the time baseline and does not add significant constraint on the nodal precession measurement.

3. MODELING THE DOPPLER TOMOGRAPHY (DT) SIGNAL

Both WASP-33 b and KELT-9 b have been studied with DT (Gaudi et al. 2017; Johnson et al. 2015; Watanabe et al. 2020). With the new data sets that have been taken in more recent epochs, we perform a uniform analysis to model the DT signal for the two planets. The uniform analysis will eliminate any systematics introduced by using different models.

3.1. Extracting Line Profiles (LPs)

We follow the least-square deconvolution (LSD, Kochukhov et al. 2010; Pai Asnodkar et al. 2021) method to extract line profiles (LPs). The LSD method requires a stellar template spectrum, for which we use the PHOENIX BT-Settl model (Allard et al. 2012, 2013, and references therein). We do not interpolate between stellar parameters. Instead, we use the spectra whose effective temperature, surface gravity, and metallicity are the closest to the reported values for WASP-33 b and KELT-9 b, i.e., $T_{\text{eff}} = 7400$ K, log$g = 4.0$, and solar metallicity for WASP-33 b, and $T_{\text{eff}} = 10200$ K, log$g = 4.0$, and solar metallicity for KELT-9 b.

The LSD method also requires a scalar value for the regularization matrix. The scalar controls the smoothness of the extracted LPs. We experiment with a wide range of possible values that span 4 orders of magnitude and choose a scalar that retains the DT signal and planet absorption signal (if visible) while removing the stochastic noise induced by the inversion process of LSD.

3.2. Removing Stellar Pulsation

WASP-33 is a $\delta$-Scuti variable star that shows a very strong stellar pulsation signal. The stellar pulsation is so strong that it overwhelms the DT signal. As detailed in Cauley et al. (2020), we apply a customized Fourier filter to remove the pulsation signal. Because the pulsation signal and the DT signal are almost orthogonal to each other, the two signals can be easily separated in
3.3. Modeling DT

We adopt an analytical framework to model the DT signal as described in Cauley et al. (2020). In short, the DT signal is a Gaussian perturbation of the stellar line profile (Hirano et al. 2011). Therefore, the DT signal can be analytically calculated and the details are described in Wang et al. (2018). The analytical framework can be applied to modeling not only the DT signal (e.g., WASP-33 b, Cauley et al. 2020), but also (1) the planet absorption signal for high-resolution spectroscopy (as shown for KELT-9 b); and (2) photometric and spectroscopic observations of eclipsing binaries (e.g., EPIC 203868608, Wang et al. 2018).

3.4. Sampling Posteriors

We used PyMultiNest (Buchner et al. 2014) for posterior sampling in a Bayesian framework. We fit each data set independently and obtain posterior samples for all parameters as described in §3.3. In this work, we focus on measuring the nodal precession as manifested by the change of projected orbital obliquity (λ) and impact parameter (b). Priors are uniform distributions between -180 degree and 180 degree for λ and between -1 and

Figure 1. From top to bottom are our modeling results for WASP-33 b data in 2008 (TULL), 2014 (TULL), 2016 (TULL), and 2019 (PEPSI). **Left:** Fourier-filtered residual map after subtracting the median line profile. The planet “Doppler shadow” is the diagonal blue track running from the bottom-right to the top-left. Occasional gaps are due to interpolation onto a time array with a fixed interval. **Middle:** Modeled DT signal. The overall gradient along the time axis is due to the shift of stellar radial velocity. The enhanced red background during transit is due to the fact that we set the line profile normalization to unity for all line profiles. **Right:** difference of the two maps on the left and middle panel.
Figure 2. From top to bottom are our modeling results for KELT-9 b data in 2014 (TRES), 2015 (TRES), 2016 (TRES), 2017 (HARPS-N), 2018 (HARPS-N), 2018 (PEPSI), and 2019 (PEPSI). **Left**: Residual map after subtracting the median line profile. The planet “Doppler shadow” is the vertical blue track due to the nearly polar orbit of KELT-9 b. The planet absorption signal is the diagonal red track that runs from bottom left to top right. The planet signal is more apparent in 2017-2019 data taken from HARPS-N and PEPSI due to a higher signal-to-noise ratio. Occasional gaps are due to interpolation onto a time array with a fixed interval. **Middle**: Modeled DT and planet absorption signal. **Right**: difference of the two maps on the left and middle panel.
1 for $b$. The likelihood function is $\exp[-(D - M)^2/E^2]$, where $D$ is data, $M$ is model, and $E$ is the error term, which we use as the standard deviation of the difference between the LPs and the median LP over time. The posterior distributions of $\lambda$ and $b$ are summarized in Table 1.

3.5. Estimating Systematics

We eliminate systematics by uniformly analyzing all data sets using the analytical modeling framework as described in previous sections. However, our model has limitations in describing physical process of a planet occulting the stellar disk. For example, the perturbation of the planet shadow to the LP may not be sufficiently described by our analytical model, which is a convolution of a rotational-broadening kernel and an Gaussian instrument profile. This could explain some of the residuals that we see in the high signal-to-noise ratio (SNR) case, e.g., the lower four panels in Fig. 2 for data from HARPS-N and PEPSI. For the low-SNR cases, e.g., 2014-2-16 data from TRES for KELT-9 b (top three panels in Fig. 2), we also notice structured residual patterns after subtracting the model from the data.

To estimate the systematics in the nodal precession measurement, we take the following two approaches. First, we have two independent data sets for KELT-9 b that are taken close in time: HARPS-N data on 2018 Jul 20 and PEPSI data on 2018 Jul 03. The difference of results for $\lambda$ and $b$ between these two data sets can be used to estimate the systematics, under the assumption that the nodal precession is smooth over time scale of a year. The difference of $\lambda$ and $b$ between the two data sets is 0.73 degree and 0.01, respectively. This is at least $\sim 4$ and $\sim 6$ times larger than the uncertainty based on the posterior from the best fit models for $\lambda$ and $b$ respectively (See Table 1).

The second approach we take is to slightly change our data analyses procedure and check how much the results vary accordingly. For example, instead of subtracting the out-of-transit median LP, we subtract the overall median LP. We find that the change in the analyses procedure can result in the change of $\lambda$ and $b$ by $\sim 2$-3 times of the reported uncertainty.

Given the above exercises in understanding the systematics in the analyses, we inflate the measurement uncertainties for $\lambda$ and $b$ to 0.75 degree and 0.01 for cases which return lower than these uncertainties based on posterior distributions, in order to account for unknown sources of systematics.

4. MODELING PLANETARY PRECESSION

We model the observed changes of the projected obliquity $\lambda$ and impact parameter $b$ over time, assuming precession of the nodes due to tidal interactions between the planets and their host stars. Our analysis is similar to that discussed in previous works (e.g., Watanabe et al. 2020; Borsa et al. 2021). We translate the observed values of $\lambda$ and $b$ into values for the ascending node versus the line-of-sight, $\Omega$, and the inclination of the planetary orbital plane versus the line of sky, $I$, via the equations

$$\tan \Omega = - \sin \lambda \tan i_p$$  \hspace{1cm} (1)

and

$$\cos I = \cos \lambda \sin i_p ,$$  \hspace{1cm} (2)

where $i_p$ is the angle between the observer’s line-of-sight and the planet’s angular momentum. The latter can be derived given the impact parameter $b$ and the ratio of the planetary orbit’s semi-major axis to the star’s radius, $(a/R_*)$, via

$$b = (a/R_*) \cos i_p .$$  \hspace{1cm} (3)

The values for these parameters for the different observation dates are shown in Table 1. The geometry of these various angles is shown in Fig. 3.

The long-term precession of the longitude of the ascending node, $\Omega$, and inclination, $I$, of any planet with significantly smaller orbital angular momentum than its host star’s stellar rotational angular momentum can be described by the equations (e.g., Iorio 2016)

$$\dot{\Omega} = - \frac{3 \pi J_2 R_*^2}{2Pa^2} \{ 2 \sin i_\star \cos i_\star \cos 2I \csc I \cos \Omega \}$$

$$- \cos I \{ 1 - 3 \sin^2 i_\star + \cos^2 i_\star \cos 2\Omega \},$$  \hspace{1cm} (4)

and

$$\dot{i} = - \frac{3 \pi J_2 R_*^2}{Pa^2} \cos i_\star \sin \Omega \{ \sin i_\star \cos I$$

$$- \cos i_\star \sin I \cos \Omega \},$$  \hspace{1cm} (5)

with $i_\star$ being the angle of the star’s rotation axis to the line-of-sight of the observer, $P$ being the planet’s orbital period, $a$ being the planet’s orbital semi-major axis, $R_*$ being the stellar radius, and $J_2$ being the star’s quadrupole gravitational moment. The values of most of these parameters are taken from the previous literature and are listed in Table 2.

We use Equations 4 and 5 to calculate the evolution of $\Omega$ and $I$ over time and fit them to our observed data in Table 1 via maximum likelihood estimation, with $i_\star$, $J_2$, $\Omega_0$, and $I_0$ as free parameters to be determined by the best-fit solution. To determine the confidence intervals for these parameters we use the MCMC code emcee (Foreman-Mackey et al. 2013).
In Figure 5, with a precession period of roughly 1460 years for the ascending node. In Figure 5 we show the earliest measured values and uncertainties for Ω and I to the WASP-33 b data, as shown in Table 1, with inflated uncertainties as explained in Section 3.5. We use additional orbital constraints from Ahlers et al. (2020) in our modeling analysis. They observed KELT-9 b (2nd analysis procedure) to be

We apply the model discussed in the previous section to the WASP-33 b data, as shown in Table 1, with inflated uncertainties as explained in Section 3.5. We use the earliest measured values and uncertainties for Ω and I as priors for Ω₀ and I₀, From the posterior we determined 1-σ confidence intervals (determined by the 16th, 50th, and 84th percentiles) and best-fit model values of J₂, iₑ, Ω₀, and I₀, which we list in Table 3 (see Figure 4 for a visualization of the probability distributions).

These values translate to the precession model shown in Figure 5, with a precession period of roughly 1460 years for the ascending node. In Figure 5 we show the evolution of the ascending node Ω, inclination of the orbital plane to the sky I, inclination of the planet’s orbit to the line-of-sight iₑ, and impact parameter b, respectively. Note that the planet can only transit in respect to an Earth-bound observer if b is between −1 and 1 (excluding “grazing” transits). Based on our model estimates, WASP-33 b’s impact parameter will dip below −1 around the year 2090 and cease to transit for approximately 500 ± 200 years (see last frame of Figure 5). Overall, WASP-33 b only transits for about 20 % of its precession period.

4.2. KELT-9 b

Similar to our analysis of the WASP-33 system discussed above, we apply our model to the KELT-9 b data from the 1st analysis procedure, as shown in Table 1, with inflated uncertainties as explained in Section 3.5. We use additional orbital constraints from Ahlers et al. (2020) in our modeling analysis. They observed KELT-9 b’s transit light curve to be clearly asymmetric, from which they were able to constrain the value of iₑ to be

\[iₑ,_{Ahlers} = 142 \pm 2 \, \text{deg}\]

We thus performed our model fit using \(iₑ,_{Ahlers}\) as prior. From the posterior we deter-
Figure 3. Geometry of the orbital elements and observables as defined in this study. The observer’s line of sight is defined as the $y$-axis, with the sky defined along the $xz$ plane. The stellar spin axis is defined to be on the $yz$ plane (see solid red arrow), forming an angle $i^*$ with the line of sight. If the star is viewed equator-on, $i^* = 90$ deg. The orbital angular momentum vector of the planet (see green solid arrow) forms an angle $i_p$ with the line of sight and an angle $I$ with the $z$-axis ($I$ is also the inclination between the orbital plane and the $xy$ plane). The projection of the orbital angular momentum vector onto the $xz$ plane defines the planet’s projected obliquity versus the $z$ axis, $\lambda$, while the projection of the vector onto the $xy$ plane defines the ascending node versus the line of sight, $\Omega$. See also Watanabe et al. (2020), Figure 4., on which this graphic is based.

Table 2. Stellar and Planetary Parameters of WASP-33 and KELT-9 from the Literature used for the Nodal Precession and Tidal Evolution Models.

| Parameter            | Value                   | Reference               |
|----------------------|-------------------------|-------------------------|
| $V \sin i_*$ (km/sec)| $86.63_{+0.37}^{-0.32}$ | Johnson et al. (2015)   |
| $a/R_*$              | $3.69 \pm 0.01$         | Collier Cameron et al. (2010b) |
| $R_p/R_*$            | $0.1143 \pm 0.0002$     | Collier Cameron et al. (2010b) |
| $R_*$ ($R_\odot$)    | $1.444 \pm 0.034$       | Collier Cameron et al. (2010b) |
| $M_p$ ($M_{Jup}$)    | $2.81 \pm 0.53$         | von Essen et al. (2014)  |
| $M_*$ ($M_\odot$)    | $1.495 \pm 0.031$       | Collier Cameron et al. (2010b) |
| $P$ (days)           | $1.2198675 \pm 0.0000011$ | von Essen et al. (2014)  |

WASP-33

| Parameter            | Value                   | Reference               |
|----------------------|-------------------------|-------------------------|
| $V \sin i_*$ (km/sec)| $111.4 \pm 1.3$         | Gaudi et al. (2017)     |
| $a$ (AU)             | $0.03462_{-0.00093}^{+0.00110}$ | Gaudi et al. (2017)    |
| $R_p$ ($R_{Jup}$)    | $1.891_{-0.053}^{+0.061}$ | Gaudi et al. (2017)     |
| $R_*$ ($R_\odot$)    | $2.365_{-0.063}^{+0.075}$ | Gaudi et al. (2017)     |
| $M_p$ ($M_{Jup}$)    | $2.88 \pm 0.84$         | Gaudi et al. (2017)     |
| $M_*$ ($M_\odot$)    | $2.52_{-0.20}^{+0.25}$   | Gaudi et al. (2017)     |
| $P$ (days)           | $1.4811235 \pm 0.0000011$ | Gaudi et al. (2017)    |

KELT-9

mined 1-$\sigma$ confidence intervals (determined by the 16th, 50th, and 84th percentiles) and best-fit model values of $J_2$, $i_*$, $\Omega_0$, and $I_0$, which we list in Table 3 (see Figure 6 for a visualization of the probability distributions).

Figure 7 shows the precession evolution based on these fit values, with a precession period of roughly $890_{-140}^{+200}$ years for the ascending node. Like WASP-33 b, KELT-9 b will eventually precess such that it will no longer transit its star from the perspective of an Earth-bound observer, which we estimate will occur around the year $2074_{-10}^{+12}$ CE. KELT-9 b will reappear as a transiting planet approximately $300 \pm 100$ years afterwards.

We also fit the data with no priors. The resulting posterior distributions are completely consistent with those
Figure 4. Corner plot of MCMC-determined values for $i_*$, $\log_10(J_2)$, $\Omega_0$, and $I_0$ of WASP-33 b. The black, dashed lines mark the 1-σ confidence interval for the values of each parameter, while the blue lines mark the parameter values of the best-fit model solution. See Table 3 for parameter values.

shown in Fig. 6. The model fit using no priors is provided in the Appendix for comparison.

5. DISCUSSION

5.1. Improvements on Previous Results and New Findings

One of the goals of this study was to improve upon the established results for the orbital parameters of WASP-33 b and KELT-9 b by previous works (e.g., Johnson et al. 2015; Gaudi et al. 2017; Watanabe et al. 2020), given the longer baseline for observations and making use of the measured nodal precession of the planets’ orbits. As such, we confirm for WASP-33 b that $i_*$ is close to 90 deg, and determine a best-fit value for $J_2$ significantly lower compared to previous works with shorter baselines (e.g., Watanabe et al. 2020), and consistent with recent work with similar extended baseline coverage (Borsa et al. 2021) (see also Table 3).

For KELT-9 b our work presents the first clear detection of the precession of KELT-9 b. We determine a very large $J_2$ value for KELT-9. We caution that the measurement of $i_*$ was complicated due to the variety of observational instruments used for observations. By using the prior based on previous work by Ahlers et al. (2020), we confirm that its best-fit value must be close to 140 deg. Furthermore, The measured precession rate of approximately $-0.3$ deg per year is consistent with previous predictions by Ahlers et al. (2020).

A crucial contribution of our study to the understanding of WASP-33 b and KELT-9 b is in the exploration of both planets’ tidal evolution, which we explore more in the following section.
literature values (references)

first detection by this work

5.2. Tidal and Orbital Evolution

Our observations have clearly shown the tidal influence on the precession of the ascending nodes of the orbits for both WASP-33 b and KELT-9 b, with best-fit values for $J_2$, the stellar gravitational quadrupole moments, of $5.92 \times 10^{-5}$ and $3.38 \times 10^{-4}$, respectively. These values are in line with expected $J_2$ values for fast-spining stars, which create their quadrupole moments via their oblateness as a response to their rapid rotation (e.g., Kraft 1967; Ward et al. 1976). The interplay of rotation and internal mass-redistribution is a highly complex phenomenon that depends on factors such as the size of a star’s radiative and convective regions, differential rotation rates, magnetic field strengths, and many more. Based on our best-fit parameter results derived from the orbital precession, and defining the stellar oblateness $f$ via the flattening formula (Murray & Dermott 2000),

$$ f = \frac{\Omega_s^2 R_*^3}{2G M_*^2} + \frac{3}{2} J_2, $$

with $\Omega_s$ being the stellar angular spin frequency, we estimate the stellar oblatenesses of WASP-33 and KELT-9 to be approximately $0.0185 \pm 0.0025$ and $0.07 \pm 0.01$, respectively. Our estimate for KELT-9 is consistent with the previous estimate by Ahlers et al. (2020) of $0.087 \pm 0.017$.

In our further analysis we are mostly interested in the tidal interactions between the stars and their planets, in particular in terms of the planets’ past and future dynamical evolution. Our data clearly shows very strong spin-orbit misalignments. This puts limits on the
strengths of the tidal dissipation within the stars that naturally would work towards realignment.

To estimate these tidal strengths, we assume the equilibrium tide model (following equations by Hut 1980; Eggleton et al. 1998). In this model an orbiting body raises a tidal bulge on its companion that either lags or leads the bulge-raising object by an angle, which is determined by the ratio of the spin period to the orbital period. In such a situation, dissipative forces then act to both synchronize the spin and orbital periods, as well as realign the orbital inclination and spin axis. The nature of these dissipative forces, however, are not well understood for many objects; in particular, the equation of state and internal structure can majorly impact the strengths of such forces. Previous works have shown that a strong distinction exists between mostly radiative versus mostly convective stars (for an overview, see Ogilvie 2014), with radiative stars generally having much weaker dissipative forces.

We test both the orbits of WASP-33 b and KELT-9 b using the equilibrium tides model. We determine that only the weaker dissipative forces for mostly radiative stars can allow their planets to exist at their current orbital configurations for an extended period of time. This result is not surprising, as both WASP-33 and KELT-9 are rather large and hot stars, and should both have radiative envelopes. Additionally, we estimate that the tidal dissipation forces acting within the planets vastly out-scale (by at least 5 orders of magnitude during peak migration) the forces within the stars. As such, we determine that (1) the planets’ spin periods must be synchronized to their orbital periods, (2) the planet’s spin and orbital axes are aligned, and (3) the planetary orbits have no residual eccentricities.

Moreover, we can estimate the timescale of migration. We can assume that the planets were originally formed further away from their hosts and migrated inwards...
via high-eccentricity migration, which can be caused by a scattering event or secular mechanisms such as the Kozai-Lidov effect by currently unseen companions (Kozai 1962; Lidov 1962; Naoz 2016). This scenario is consistent with the observed large spin-orbit misalignment.

Starting with original orbital semi-major axes from 1 to 10 AU, migration and circularization at their currently observed orbital separations would take approximately 30 to 100 Myrs for WASP-33 b and 40 to 120 Myrs for KELT-9 b, assuming the equilibrium tide model\(^2\). These time scales are not unrealistic given the estimated ages of roughly 100 Myrs for WASP-33 and 300 Myrs for KELT-9 (e.g., Collier Cameron et al. 2010b; Gaudi et al. 2017). However, this would imply that migration began very soon after planet formation.

These migration scenarios would require a significant dissipation of energy by the planets as heat, reaching on the order of \(L_p \sim 10^{30}\) ergs/second during the fastest migration episodes, or \(\sim 0.1\%\) of \(L_\odot\), the solar energy output. This energy dissipation is well within realistic levels and would not heat the planets to more than about 2500 K during peak migration. This calculation ignores additional heat sources and assumes black-body radiation. As the current day-side temperatures of both planets caused by their host stars’ incoming irradiation is higher than that, the tidal energy would not significantly alter the planets’ chemistry or internal structure. However, if the planets still have any residual internal energy from migration, it could show up as higher-than expected night-side temperatures. If such a discrepancy exists, it would be a telltale sign for migration and allow us to estimate how recently migration must have occurred, with the caveat that winds and other energy transport mechanisms in the planetary atmospheres could dilute such a signal. High night-side temperatures on the order of 2500 K to 3000 K have indeed been observed for exoplanets TOI-1431 b/MASCARA-5 b (Addison et al. 2021) and KELT-9 b (Wong et al. 2020), though in both cases current models explain these temperatures with atmospheric energy transport.

6. SUMMARY

Multi-epoch observations of transiting planetary systems can (1) predict the long-term dynamical evolution; and (2) infer stellar and orbital properties that are responsible for the tidal interactions within such systems.

We use multi-epoch observations to study two ultra-hot Jupiter systems: WASP-33 b and KELT-9 b. The data spans 11 and 5 years, respectively. Using the Doppler Tomography technique, we adopt an analytical framework to model the high-resolution spectroscopic data sets during the transit. Through the framework, we infer the posterior distribution of the projected obliquity \(\lambda\) and impact parameter \(b\) over time. The time-varying \(\lambda\) and \(b\) reveals that both WASP-33 b and KELT-9 b are undergoing orbital precession.

By applying a tidal interaction model to the time-varying \(\lambda\) and \(b\) data, we can constrain the \(J_2\) values for the two planet host stars (see Table 3) and predict the dynamical fate of the two systems. We determine the nodal precession periods for the orbits of WASP-33 b and KELT-9 b to be \(1460^{+170}_{−130}\) and \(890^{+200}_{−140}\) years, respectively. As such, WASP-33 and KELT-9 b are expected to cease transiting their stars around \(2090^{+117}_{−10}\) CE and \(2074^{+12}_{−10}\) CE, respectively. We furthermore find that either planet can only exist at its current orbit for an extended period of time given weak stellar tidal dissipation consistent with stars with radiative envelopes. The weak tidal dissipation also allows for the observed high stellar spin-orbit misalignments. As such, most tidal dissipation within these systems occurs within the planets, implying planetary spin-orbit alignment and synchronization. If the planets reached their current orbital configurations due to high-eccentricity migration, such migration would have occurred on time scales of a few tens to a hundred Myrs. We estimate that the planets can exist at approximately their current orbital configurations for the remaining main-sequence lifetimes of their host stars, to be eventually engulfed during post-MS inflation.

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\(^2\) We note here that these time scales depend on the assumed value of the viscous timescale \(t_v\), which is usually estimated to be on the order of years or decades for stars and gas giants, as well as the exact nature of the eccentricity-inducing mechanism.
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APPENDIX

A. PRECESSION MODEL FIT FOR KELT-9 B WITHOUT PRIORS

As mentioned in Section 4.2, our observations for KELT-9 b most likely contained some unknown uncertainties that made fitting the model to the data without additional priors difficult. Here, we provide our model fit to the data using no priors as a comparison to our cited results in Section 4.2 using the Ahlers et al. (2020) prior. Using no priors for the MCMC results in 1-σ confidence intervals for the values of the tidal parameter, \( J_2 = (3^{+1.8}_{-0.8}) \times 10^{-4} \), of the stellar spin axis angle versus the line-of-sight, \( \iota_\ast = 104^{+30}_{-34} \) deg, of the initial longitude of the ascending node, \( \Omega_0 = 87.50^{+0.19}_{-0.19} \) deg, and of the initial inclination, \( I_0 = 85.53^{+0.54}_{-0.64} \) deg (see Figure 8). These values correspond to the precession evolution shown in Figure 9. However, the large uncertainty in the value of \( \iota_\ast \) highlights the limited information content of the data. In particular, the scatter in the observed inclination (\( I \)) values (see Figure 9, second row, left frame), on the same order as the uncertainties, makes finding an appropriate model fit challenging.

REFERENCES

Addison, B. C., Knudstrup, E., Wong, I., et al. 2021, AJ, 162, 292
Ahlers, J. P., Johnson, M. C., Stassun, K. G., et al. 2020, AJ, 160, 4
Figure 9. Evolution of the ascending node $\Omega$ (first row), inclination $I$ (second row), the planet’s orbital inclination versus the observer’s line-of-sight $i_p$ (third row), and impact parameter $b$ (fourth row) over time for KELT-9 b, using no priors for the fitting model. Dark blue downward triangles and error bars show TRES data, yellow squares and error bars show HARPS-N data, and green dots and error bars show PEPSI data. The black line shows the best-fit model, with red lines showing 2000 example models with model likelihoods within the 1-$\sigma$ confidence interval around the best-fit model.

Albrecht, S., Winn, J. N., Johnson, J. A., et al. 2012, ApJ, 757, 18
Allard, F., Homeier, D., & Freytag, B. 2012, Philosophical Transactions of the Royal Society of London Series A, 370, 2765
Allard, F., Homeier, D., Freytag, B., et al. 2013, Memorie della Societa Astronomica Italiana Supplementi, 24, 128
Barnes, J. W., van Eyken, J. C., Jackson, B. K., Ciardi, D. R., & Fortney, J. J. 2013, ApJ, 774, 53
Borsa, F., Lanza, A. F., Raspantini, I., et al. 2021, A&A, 653, A104
Buchner, J., Georgakakis, A., Nandra, K., et al. 2014, A&A, 564, A125
Cauley, P. W., Shkolnik, E. L., Ilyin, I., et al. 2019, AJ, 157, 69
Cauley, P. W., Wang, J., Shkolnik, E. L., et al. 2020, arXiv e-prints, arXiv:2010.02118
Charpinet, S., Fontaine, G., Brassard, P., et al. 2011, Nature, 480, 496
Collier Cameron, A., Guenther, E., Smalley, B., et al. 2010a, MNRAS, 407, 507
—. 2010b, MNRAS, 407, 507
Eggleton, P. P., Kiseleva, L. G., & Hut, P. 1998, ApJ, 499, 853
Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306
Gaudi, B. S., Stassun, K. G., Collins, K. A., et al. 2017, Nature, 546, 514
Gettel, S., Wolszczan, A., Niedzielski, A., et al. 2012, ApJ, 745, 28
Hirano, T., Suto, Y., Winn, J. N., et al. 2011, ApJ, 742, 69
Hoeijmakers, H. J., Ehrenreich, D., Kitzmann, D., et al. 2019, A&A, 627, A165
Howard, A. W., Marcy, G. W., Bryson, S. T., et al. 2012, ApJS, 201, 15
Hut, P. 1980, A&A, 92, 167
Iorio, L. 2016, MNRAS, 455, 207
Johnson, M. C., Cochran, W. D., Collier Cameron, A., & Bayliss, D. 2015, ApJL, 810, L23
Kawaler, S. D. 1988, ApJ, 333, 236
Kochukhov, O., Makaganiuk, V., & Piskunov, N. 2010, A&A, 524, A5
Kozai, Y. 1962, AJ, 67, 591
Kraft, R. P. 1967, ApJ, 150, 551
Lidov, M. L. 1962, planss, 9, 719
Meynet, G., Eggenberger, P., & Maeder, A. 2011, A&A, 525, L11
Murray, C. D., & Dermott, S. F. 2000, Solar System Dynamics, ed. Murray, C. D. & Dermott, S. F.
Nagasawa, M., Ida, S., & Bessho, T. 2008, ApJ, 678, 498
Naoz, S. 2016, ARA&A, 54, 441
Naoz, S., Farr, W. M., Lithwick, Y., Rasio, F. A., & Teyssandier, J. 2011, Nature, 473, 187
—. 2013, MNRAS, 431, 2155
Naoz, S., Farr, W. M., & Rasio, F. A. 2012, ApJL, 754, L36
Niedzielski, A., Wolszczan, A., Nowak, G., et al. 2015, ApJ, 803, 1
Niedzielski, A., Villaver, E., Nowak, G., et al. 2016, A&A, 589, L1
Nowak, G., Niedzielski, A., Wolszczan, A., Adamów, M., & Maciejewski, G. 2013, ApJ, 770, 53
Ogilvie, G. I. 2014, ARA&A, 52, 171
Pai Asnodkar, A., Wang, J., Eastman, J. D., et al. 2022a, arXiv e-prints, arXiv:2201.04154
Pai Asnodkar, A., Wang, J., Gaudi, B. S., et al. 2021, arXiv e-prints, arXiv:2110.15275
—. 2022b, AJ, 163, 40
Quirrenbach, A., Amado, P. J., Ribas, I., et al. 2018, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 10702, Ground-based and Airborne Instrumentation for Astronomy VII, ed. C. J. Evans, L. Simard, & H. Takami, 107020W
Reffert, S., Bergmann, C., Quirrenbach, A., Trifonov, T., & Künstler, A. 2015, A&A, 574, A116
Strassmeier, K. G., Ilyin, I., Järvinen, A., et al. 2015, Astronomische Nachrichten, 336, 324
Tull, R. G., MacQueen, P. J., Sneden, C., & Lambert, D. L. 1995, PASP, 107, 251
von Essen, C., Czesla, S., Wolter, U., et al. 2014, A&A, 561, A48
Wang, J., David, T. J., Hillenbrand, L. A., et al. 2018, ApJ, 865, 141
Ward, W. R., Colombo, G., & Franklin, F. A. 1976, Icarus, 28, 441
Watanabe, N., Narita, N., & Johnson, M. C. 2020, PASJ, 72, 19
Winn, J. N., & Fabrycky, D. C. 2015, ARA&A, 53, 409
Wong, I., Shporer, A., Kitzmann, D., et al. 2020, AJ, 160, 88
Yan, F., Casasayas-Barris, N., Molaverdikhani, K., et al. 2019, A&A, 632, A69