Variable and Supersonic Winds in the Atmosphere of an Ultrahot Giant Planet

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Abstract

Hot Jupiters (HJs) receive intense irradiation from their stellar hosts. The resulting extreme environments in their atmospheres allow us to study the conditions that drive planetary atmospheric dynamics, e.g., global-scale winds. General circulation models predict day-to-nightside winds and equatorial jets with speeds of the order of a few km s$^{-1}$. To test these models, we apply high-resolution transmission spectroscopy using the Potsdam Echelle Polarimetric and Spectroscopic Instrument (PEPSI) spectrograph on the Large Binocular Telescope to study the atmosphere of KELT-9 b, an ultrahot Jupiter and currently the hottest known planet. We measure $\sim$10 km s$^{-1}$ day-to-nightside winds traced by Fe II features in the planet’s atmosphere. This is at odds with previous literature (including data taken with PEPSI), which report no significant day-to-nightside winds on KELT-9 b. We identify the cause of this discrepancy as due to an inaccurate ephemeris for KELT-9 b in previous literature. We update the ephemeris, which shifts the midtransit time by up to 10 minutes for previous data sets, resulting in consistent detections of blueshifts in all the data sets analyzed here. Furthermore, a comparison with archival data sets from the High-accuracy Radial velocity Planet Searcher for the Northern hemisphere suggests a temporal wind variability of $\sim$5–8 km s$^{-1}$ over timescales between weeks to years. Temporal variability of atmospheric dynamics on HJs is a phenomenon anticipated by certain general circulation models that has not been observed over these timescales until now. However, such large variability as we measure on KELT-9 b challenges general circulation models, which predict much lower amplitudes of wind variability over timescales between days to weeks.

Unified Astronomy Thesaurus concepts: Exoplanet astronomy (486); Exoplanet atmospheres (487); Exoplanet atmospheric variability (2020); Exoplanets (498)

1. Introduction

Among transiting exoplanets, hot Jupiters (HJs) are the most accessible and exotic class of planets for atmospheric characterization. Their large size and proximity to their host stars establishes them both as ideal targets for transit techniques and unique laboratories for exploring the interplay between radiative, chemical, and dynamical processes in gas-giant atmospheres. Transmission and emission spectroscopy studies suggest that more highly irradiated HJ atmospheres display a diversity of thermal structures.

Recent efforts in exoplanet characterization seek empirical constraints on HJ atmospheric circulation (Snellen et al. 2010; Ehrenreich et al. 2020; Cauley et al. 2021). Atmospheric dynamics are a critical form of energy transport and significantly contribute to the full energy budget of highly irradiated exoplanet atmospheres. The strong temperature contrast between the day and nightsides of HJs drives global day-to-nightside winds and superrotating equatorial jets. General circulation models (GCMs) of classic HJs like HD 209458 b or HD 189733 b predict strong ($\sim$1–3 km s$^{-1}$) day-to-nightside winds (Showman et al. 2013). Equatorial jets ($\sim$3–4 km s$^{-1}$) are predicted to offset the dayside hotspot eastward of the substellar point (Showman et al. 2008; Showman & Polvani 2011). Notably, few GCMs that explore low-pressure dynamics exist, especially in the millibar to $\mu$bar range relevant to high-resolution transmission spectroscopy observations (Hoeijmakers et al. 2019).

GCM predictions for HJs have been validated by phase-curve observations (Knutson et al. 2007; Kataria et al. 2016; Wong et al. 2020) and high-resolution Doppler spectroscopy (Snellen et al. 2010; Louden & Wheatley 2015). Global day-to-nightside winds can be probed with transmission spectroscopy between the 2nd and 3rd contact of a transit to measure the terminator-averaged spectrum of the planet’s atmosphere. During transit, day-to-nightside winds manifest as lines that are blueshifted relative to the planet’s orbital velocity. Empirical measurements of these winds on HJs thus far corroborate the $\sim$few km s$^{-1}$ prediction from GCMs. The first such measurement was traced by CO absorption in the near-infrared, revealing $2 \pm 1$ km s$^{-1}$ day-to-nightside winds on HD 209458 b (Snellen et al. 2010). A study of CO and H$_2$O absorption features retrieved day-to-nightside wind speeds of 1.7$^{+1.2}_{-1.3}$ km s$^{-1}$ on HD 189733 b (Brogi et al. 2016). Wind velocity and hotspot offset measurements provide direct evidence for the extremity and relevance of atmospheric dynamics in shaping the thermal structure of highly irradiated giant planets. Atmospheric dynamics in HJs can also have first-order effects on the template spectra that should be used in the analysis and interpretation of high-resolution spectroscopy observations (Flowers et al. 2019; Beltz et al. 2021a).

In this work, we report on the atmospheric dynamics of KELT-9 b (Gaudi et al. 2017) and KELT-20 b (Lund et al. 2017; Talens et al. 2018), both of which fall in a categorically
distinct class of objects known as ultrahot Jupiters (UHJs). The unique atmospheric thermal structures and chemical composition of giant planets with \( T_{\text{eq}} \gtrsim 2500 \) K motivate this separate class of HJs. Most notably, thermal inversions (regions of the atmosphere analogous to Earth’s stratosphere where temperature increases with decreasing pressure, i.e., increasing altitude) only occur in the hottest HJs. The majority of ultrahot Jupiters display nearly isothermal pressure–temperature (P–T) profiles around millibar pressures and lower (Lothringer & Barman 2019), while some decrease outward in temperature (Madhusudhan 2019). A small subset of UHJs exhibit evidence of thermal inversions, including the classic examples WASP-18 b (Sheppard et al. 2017), WASP-121 b (Evans et al. 2017), WASP-33 b (Haynes et al. 2015), and our target of focus, KELT-9 b (Pino et al. 2020).

UHJs are further distinguished by their composition and lack of molecular features (e.g., water, molecular hydrogen) due to dissociation at extreme temperatures. Extending giant planet GCMs to the extreme P–T regime of UHJs requires introducing additional chemistry due to the dissociation of molecular hydrogen and magnetic effects due to metal ionization. For this reason, UHJs are challenging to model and are relatively new territory in GCM literature. Accounting for the thermodynamic effect of \( \mathrm{H}_2 \) dissociation has been shown to horizontally (i.e., across longitudes) homogenize heat redistribution (Roth et al. 2021), resulting in weaker day-to-nightside winds than expected without dissociation (Tan & Komacek 2019). Wind measurements may answer questions regarding the role of second-order effects in UHJ atmospheres like molecular dissociation and magnetic drag from thermally ionized winds (Perna et al. 2010; Rogers & Komacek 2014).

Previous studies of atmospheric dynamics on KELT-9 b report no significant day-to-nightside winds (Yan & Henning 2018; Cauley et al. 2019; Hoeijmakers et al. 2019; Yan et al. 2019; Wytenbach et al. 2020). In this work, we present new day-to-nightside wind measurements of KELT-9 b that challenge previous measurements and theoretical predictions. We employ two epochs of observations from the Potsdam Echelle Polarimetric and Spectrographic Instrument (PEPSI; Strassmeier et al. 2015) on the Large Binocular Telescope (LBT). We apply both a high-resolution line-by-line analysis and the cross-correlation technique to study the Doppler signature of Fe II in the atmosphere of KELT-9 b. We compare the PEPSI findings with archival data from the High-accuracy Radial velocity Planet Searcher for the Northern hemisphere (HARPS-N) originally presented in Hoeijmakers et al. (2019). We also validate our methods against previous literature using KELT-20 b as a test case. We discuss our wind measurements across techniques and data sets, compare with previous literature, and discuss the consequences for GCMs of UHJs.

2. Methods

Our methodology is presented in greater detail in our previous paper (Pai Asnodkar et al. 2022), but we will summarize the key points here. We compile observations of the KELT-9 system from the high-resolution spectrograph PEPSI (\( R = 50,000 \)) on the LBT (see Figure 1) and archival data from HARPS-N (\( R = 115,000 \)) on Telescopio Nazionale Galileo (TNG). Our analysis of PEPSI data exclusively employs observations from the blue arm with cross disperser 3 (\( \sim 4750–5430 \) Å). For comparison, we select the same wavelength range in our examination of the HARPS-N data. As a test, we also perform a homogeneous analysis of KELT-20 b’s atmospheric dynamics traced by the same six Fe II lines and wavelength range for cross correlation we investigate in KELT-9 b’s atmosphere. We analyze an original PEPSI data set as well as archival HARPS-N observations of the KELT-20 system. We refer to the KELT-9 b data sets by their instrument and year of observation (HARPS-N 2017, PEPSI 2018, HARPS-N 2018, PEPSI 2019, and HARPS-N 2018 in chronological order). To avoid confusion, we refer to the KELT-20 data sets by their instrument and full date of observation (HARPS-N 20170816, HARPS-N 20180712, HARPS-N 20180719, and PEPSI 20190504). Further details about the observations are presented in Table 1 and Section 2 of Pai Asnodkar et al. (2022).

We employ transmission spectroscopy to probe the atmospheric dynamics of KELT-9 b and KELT-20 b. We apply least-squares deconvolution (Section 3.1 of Pai Asnodkar et al. 2022) on out-of-transit observations to determine stellar radial velocities and fit for a circular stellar orbital solution to quantify the systemic velocities for both systems as individually measured by the PEPSI and HARPS-N instruments (\( \nu_{\text{sys,PEPSI}} = -17.86 \pm 0.044 \) km s\(^{-1}\) and \( \nu_{\text{sys,HARPS-N}} = -17.15 \pm 0.11 \) km s\(^{-1}\)). We divide out the stellar component encapsulated by the out-of-transit observations to recover the transmission spectra and isolate the planet’s atmospheric absorption signature (Section 3.2 of Pai Asnodkar et al. 2022). We perform both a line-by-line analysis and
cross-correlation analysis of the fully in-transit observations to avoid asymmetries and velocity offsets from equatorial jets and rotation during ingress/egress (Yan & Henning 2018; Casayas-Barris et al. 2020; Cauley et al. 2021). We generate a grid of models of the secondary effects from the Rossiter–McLaughlin effect (RME) and center-to-limb variation. We simultaneously fit the in-transit secondary effects and planetary atmospheric absorption signatures from individual Fe II lines and cross correlation. We model the planet’s absorption as a Gaussian feature shifted according to a circular orbital solution modified by a constant blueshift ($v_{\text{wind}}$) due to day-to-nightside winds. See Pai Asnodkar et al. (2022) for more details.

A critical aspect in our analysis of the KELT-9 system is our revised ephemeris. We refit the KELT-9 system with EXOFASTv2 (Eastman et al. 2019) to include Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) light curves from 2019 in addition to the followup light curves and TRES RVs from the discovery paper. The updated ephemeris is critical for this analysis as the observations span multiple years and precision deteriorates as the ephemeris is propagated over a longer temporal baseline. In our analysis of KELT-20 b, we adopt the system ephemeris given in Lund et al. (2017); the Talens et al. 2018 ephemeris does not yield significantly different wind velocities). We do not update the KELT-20 ephemeris because the analysis of its atmospheric dynamics is less sensitive to midtransit timing due to its slower orbital velocity and larger orbital period.

3. Results

The left panel of Figure 2 summarizes the global day-to-nightside winds observed in KELT-9 b’s PEPSI 2018 and PEPSI 2019 data sets. Across the six different Fe II lines we inspected, the measurements are generally consistent within a given data set. However, there is a systematic offset between the 2018 and 2019 measurements. The error-weighted median value with 1σ errors of the 2018 and 2019 measurements across all six lines are $-8.79^{+0.56}_{-0.88}$ km s$^{-1}$ and $-11.59^{+1.36}_{-1.13}$ km s$^{-1}$, respectively.

We also measure day-to-nightside winds from the two PEPSI data sets as traced by Fe II absorption using cross correlation. This analysis yields $-9.55^{+0.56}_{-0.88}$ km s$^{-1}$ and $-10.41^{+0.64}_{-0.57}$ km s$^{-1}$ for the PEPSI 2018 and PEPSI 2019 data sets, respectively. Thus the cross-correlation measurements are consistent with the line-by-line analysis of their corresponding data sets.

In contrast, the HARPS-N measurements taken from cross correlation differ by a significant $\sim$5–8 km s$^{-1}$ offset. In particular, the PEPSI 2018 and HARPS-N 2018 data sets were both taken in July and differ by 5.7σ (5.3 km s$^{-1}$). This discrepancy is not attributable to an RV offset between the two instruments as the systemic velocities we obtain for both instruments from our analysis of stellar RVs are consistent within 1 km s$^{-1}$. As there is no evidence to date of a companion in the system to cause significant transit-timing variations and upon confirming that our conversion to the BJD$_{\text{TDB}}$ timing system for all data sets was applied correctly (see Section 2 of Pai Asnodkar et al. 2022), we conclude that this discrepancy in our velocity measurements is most plausibly astrophysical. The discrepancy suggests multiepoch temporal variability of global day-to-nightside winds on KELT-9 b.

Table 1

| Target | Instrument | Night       | $t_{\text{start}}$ (UTC) | $t_{\text{end}}$ (UTC) | $N_{\text{obs}}$ |
|--------|------------|-------------|---------------------------|------------------------|-----------------|
| KELT-9 b | HARPS-N    | 2017-07-31  | 20:59:04.0                | 05:19:10.0             | 49              |
|        | PEPSI      | 2018-07-03  | 04:07:34.4                | 11:16:41.3             | 82              |
|        | HARPS-N    | 2018-07-20  | 21:20:24.0                | 05:09:58.0             | 46              |
|        | PEPSI      | 2019-06-22  | 05:19:33.7                | 11:29:06.5             | 65              |
| KELT-20 b | HARPS-N    | 2017-08-16  | 22:26:04.7                | 04:00:39.4             | 90              |
|        | HARPS-N    | 2018-07-12  | 21:27:47.4                | 05:14:51.9             | 116             |
|        | HARPS-N    | 2018-07-19  | 21:26:28.1                | 04:24:36.4             | 78              |
|        | PEPSI      | 2019-05-04  | 07:23:06.0                | 11:57:55.7             | 22              |

4. Discussion

4.1. Comparison with Previous Literature

Using the HARPS-N data sets, our results are blueshifted relative to the measurements in Hoeijmakers et al. (2019) by $\sim$4 km s$^{-1}$. They originally measured no significant atmospheric blueshift with these same data (statistically consistent with $v_{\text{wind}} = 0$ km s$^{-1}$) as traced by numerous metal species, including Fe II, using cross correlation. We can account for this discrepancy due to our revised midtransit time ephemeris; see Table 2 (also given as Table 2 in Pai Asnodkar et al. 2022). The revised ephemeris results in a propagated midtransit time that is 4.2 minutes earlier for the HARPS-N 2017 epoch and 5.8 minutes earlier for the HARPS-N 2018 epoch than the original ephemeris presented in Gaudi et al. (2017), which Hoeijmakers et al. (2019) adopt. According to our measurement of the orbital motion of the planet, these revised midtransit times result in day-to-nightside winds that are correspondingly blueshifted by 3.0 km s$^{-1}$ and 4.1 km s$^{-1}$ relative to the measurement using the original midtransit time ephemeris.

For a visual understanding of how midtransit timing affects the measured day-to-nightside winds, refer to Figure 3. We define orbital phase as $\phi = \frac{t - P}{P}$ such that $\phi = 0$ corresponds to midtransit. At this phase, the planet’s atmospheric signature is only shifted by the day-to-nightside winds (given that the data has been corrected for the systemic velocity, the orbital radial velocity of the planet at midtransit is 0 km s$^{-1}$). Hoeijmakers et al. (2019) found no significant day-to-nightside winds, so the velocity of the atmospheric absorption signature they measure (represented by the red solid curve in Figure 3) at $\phi = 0$ is 0 km s$^{-1}$. According to our definition of orbital phase, an earlier midtransit time effectively shifts the atmospheric absorption signature (and the whole flux map) up in phase. Based on the orientation of the atmospheric absorption signature during transit, shifting the absorption signature up in phase according to our revised ephemeris (represented by the.

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blue solid line in Figure 3) results in a more blueshifted absorption signature during midtransit and thus yields a more blueshifted measurement of day-to-nightside winds.

Likewise, Cauley et al. \((2019)\) reports no significant day-to-nightside winds on KELT-9b by studying individual metal lines including Fe II lines in the PEPSI 2018 data set. In contrast, we measure very extreme winds of the order of 8–10 km s\(^{-1}\) with the same data. Like Hoeijmakers et al. \((2019)\); Cauley et al. \((2019)\) adopt the midtransit timing ephemeris reported in Gaudi et al. \((2017)\). To address this discrepancy, we adopt the PEPSI 2018 midtransit time BJD TDB \(T_0\) reported in this work and adjust the midtransit times BJD TDB \(T_S\) and ingress/egress transit duration days \(\tau\) to agree with the ephemeris reported in Gaudi et al. \((2017)\). Consequently, the total transit duration days \(T_{14}\) is also adjusted to agree with the ephemeris reported in Gaudi et al. \((2017)\). The updated midtransit times BJD TDB \(T_0\) and \(T_S\) ensure that KELT-9b is at the same phase for midtransit and secondary eclipse observations. This adjustment reduces the day-to-nightside winds measured compared to Hoeijmakers et al. \((2019)\); Cauley et al. \((2019)\) by adjusting the midtransit time.

Figure 2. Day-to-nightside winds measurements from Fe II line-by-line and cross-correlation analyses with Markov chain Monte Carlo (MCMC) sampling errors for (a) KELT-9 b and (b) KELT-20 b. We note that the Fe II \(\lambda 5363.9\) Å line is very weak with \(S/N = 1.6\); for comparison, the Fe II \(\lambda 5169\) Å line has \(S/N = 9.0\) (see Figure 1 for the observed relative line strength of KELT-9 b as an example). Thus, this line is less reliable for measuring day-to-nightside winds.

Table 2
KELT-9 System Parameters (Reproduced from Pai Asnodkar et al. \(2022\))

| Parameter                        | Units | Symbol | Value          | Source                        |
|----------------------------------|-------|--------|----------------|-------------------------------|
| Stellar parameters:             |       |        |                |                               |
| Stellar mass                     | \(M_\odot\) | \(M_*\) | 2.52 \(\pm\) 0.25 | Gaudi et al. \((2017)\)      |
| Stellar radius                   | \(R_\odot\) | \(R_*\) | 2.362 \(\pm\) 0.07 | Gaudi et al. \((2017)\)      |
| Stellar density                  | g cm\(^{-3}\) | \(\rho_*\) | 0.2702 \(\pm\) 0.0029 | Gaudi et al. \((2017)\)      |
| Effective temperature            | K     | \(T_{\text{eff}}\) | 10170 \(\pm\) 450   | Gaudi et al. \((2017)\)      |
| Projected rotational velocity    | km s\(^{-1}\) | \(v \sin i\) | 111.4 \(\pm\) 1.3   | Gaudi et al. \((2017)\)      |
| Planetary parameters:            |       |        |                |                               |
| Planet mass                      | \(M_J\) | \(m_p\) | 2.88 \(\pm\) 0.84 | Gaudi et al. \((2017)\)      |
| Planet radius                    | \(R_J\) | \(R_p\) | 1.891 \(\pm\) 0.053 | Gaudi et al. \((2017)\)      |
| Semimajor axis                   | AU    | \(a\)  | 0.03462 \(\pm\) 0.00018 | Gaudi et al. \((2017)\)      |
| Eccentricity                     |       | \(\varepsilon\) | 0                | Gaudi et al. \((2017)\)      |
| Spin–orbit alignment             | degree | \(\lambda\) | \(\lambda\) \(\approx\) 84.8 \(\pm\) 1.4 | Gaudi et al. \((2017)\)      |
| Orbital inclination              | degree | \(\iota_{\text{orbit}}\) | 86.79 \(\pm\) 0.25 | Gaudi et al. \((2017)\)      |
| Ephemeris:                       |       |        |                |                               |
| Midtransit time                  | BJD TDB | \(T_0\)  | 2458566.436560 \(\pm\) 0.000004 | This work                    |
| Time of secondary eclipse        | BJD TDB | \(T_S\)  | 2458584.950546 \(\pm\) 0.000004 | This work                    |
| Orbital period                   | days  | \(P\)  | 1.48111290 \(\pm\) 0.000000016 | This work                    |
| Ingress/egress transit duration  | days  | \(\tau\) | 0.012808 \(\pm\) 0.000027 | This work                    |
| Total transit duration           | days  | \(T_{14}\) | 0.15949 \(\pm\) 0.00011 | This work                    |
5.7 minutes from our ephemeris when both are propagated to the PEPSI 2018 data set epoch. This yields a 4.1 km s\(^{-1}\) blueshift in our measurement of day-to-nightside winds relative to Cauley et al. (2019)’s. Furthermore, Cauley et al. (2019) neglected to convert the observation timings from the JD\(_{UTC}\) timing system to BJDTDB, which is the timing system in which the Gaudi et al. (2017) ephemeris is given. This results in an additional 4.4 minute difference, which corresponds to an additional 3.1 km s\(^{-1}\) discrepancy in our measurements. The residual difference in our measurements is \(\sim 1\)–3 km s\(^{-1}\). This difference captures the discrepancy between our derived systemic RV (\(v_{\text{sys,PEPSI}} = -17.86 \pm 0.044\) km s\(^{-1}\)) and the value adopted by Cauley et al. (2019): \(v_{\text{sys}} = -20.567 \pm 0.1\) km s\(^{-1}\) from Gaudi et al. (2017) as well as observational errors. Our reanalysis of previously presented data sets emphasizes the importance of precision timing in constraining the atmospheric dynamics of close-orbit planets.

Our revised midtransit timing ephemeris is more reliable than the value presented in Gaudi et al. (2017). As described in Section 3.1.3 of Pai Asnodkar et al. (2022), we refit the KELT-9 system with EXOFASTv2 (Eastman et al. 2019) to include recent TESS observations (Ricker et al. 2015) in addition to the followup light curves and TRES RVs from the discovery paper. The revision is especially critical for this analysis as the observations span multiple years; the error propagation using the original ephemeris can be as large as 4.8 minutes for the PEPSI 2019 data set. Incorporating the TESS 2019 data light curves to span a broader temporal baseline improves the precision of the ephemeris and mitigates the issue of “stale” ephemerides.

Wong et al. (2020) reports no significant temporal variability in KELT-9 b’s dayside hotspot from TESS light curves, which seems to at odds with our observed variability of KELT-9 b’s atmospheric dynamics. However, we note that the two observations probe different pressure levels and may not be relevant in the context of variability. The phase-curve observations probe \(\sim 1\) bar level, whereas our Fe II line observations probe pressure levels at \(\lesssim 1\) \(\mu\)bar.

4.2. Impact of Transit Fitting and Orbital Dynamics on Midtransit Timing

One nuance to address is that our global fit does not account for the distinctly observable gravity-darkening signature in the TESS transit light curves. However, Ahlers et al. (2020) similarly achieve subminute precision on the midtransit timing. They show that the midtransit timing ephemeris obtained from transit models with and without gravity-darkening differ by \(~ 0.2\) minutes. Upon personal correspondence with the first author, we confirmed that they did not place a prior on midtransit timing in their model fits (J. Ahlers, personal correspondence, 2021 August 2). Therefore, the midtransit timings of both models (with and without gravity-darkening) inherently agree well within 1\(\sigma\), especially when propagated to the different epochs of our observations. The difference of 0.2 minutes is not significant enough to yield an appreciable change in the measured day-to-nightside wind velocity as implied by Figure 3. Thus, we conclude that our midtransit timing maintains fidelity despite neglecting the photometric effects of gravity-darkening in our global fit.

Other nuances that may affect the day-to-nightside wind measurement are potential eccentricity in KELT-9 b’s orbit and nodal precession. Both of these effects yield a discrepancy between our modeled versus the true orbital motion of the planet. First, we will address eccentricity.

To extract day-to-nightside winds, we model the RV of the fully in-transit atmospheric absorption signature as a circular Keplerian orbit with an offset due to day-to-nightside winds (we remove the RV shift due to systemic velocity before performing this analysis). Over the small range of phases exposed during a transit, the RV signal is approximately linear over time. In principle, this offset may not be entirely due to day-to-nightside winds if KELT-9 b’s true orbit were sufficiently eccentric with an argument of periastris significantly offset from the midtransit point along our line of sight. From the primary and secondary eclipse timings given by the eccentric models (models 5 and 8) in Gaudi et al. (2017), we constrain \(|e \cos \omega| = 0.00170 \pm 0.00181\) using Equation (3) of
Charbonneau et al. (2005); note that this uncertainty may be underestimated as it does not account for the covariance between the primary and secondary eclipse timings. When including this constraint, we find that introducing eccentricity only changes the slope of the RV signal over the course of the transit and does not change the linearity or offset of the signal for reasonably small eccentricities (0.001 < e < 0.2). Since the slope of the signal (Kp) is a free parameter in our fit, we conclude that our model sufficiently captures the orbital motion of the planet and the offset exclusively represents the day-to-nightside winds on KELT-9 b.

Nodal precession also modifies the planet’s orbit in such a way that it could lead to a misinterpretation of our observations. Nodal precession can occur to a planet around an oblate star, where a nonzero gravitational quadrupole field causes the planet’s orbital plane to precess. Consequently, the chord across the stellar disk transited by the planet changes over the years, which changes the orbital phases over which the planet’s atmosphere is illuminated. Thus, our modeled orbital motion of the planet may not accurately capture the true orbital motion without accounting for nodal precession. The observed parameters modified by nodal precession are the impact parameter (directly related to orbital inclination by the transit observable a/R*) and spin–orbit angle, both of which can be measured by Doppler tomography. We estimate the effects of nodal precession on the orbital motion of KELT-9 b using preliminary measurements of these parameters across all four data sets (Wang & Stephan 2022). We find the greatest difference in midtransit timing due to nodal precession is between the PEPSI 2019 and HARPS-N 2017 data sets with a difference of 0.073 minutes. This is not significant enough to yield a measurable difference in wind velocity according to our prior precision timing argument. Furthermore, the transit timing and duration do not change drastically enough to yield a measurably significant difference in the observable orbital RVs of the planet during the course of the four transits. Thus, we conclude that nodal precession does not change the orbital motion of KELT-9 b enough to change the observed orbital RVs of the planet over the course of the four transits studied in this work. Additionally, the timescale of nodal precession (~thousands of years) is too long to induce variability in midtransit timing and likewise the (inaccurate) measurement of day-to-nightside winds.

4.3. Comparison with KELT-20 b

To emphasize how variability of atmospheric dynamics is unique to KELT-9 b and not an artifact of our analysis from two different instruments, we apply the same procedure to PEPSI and HARPS-N observations of another UHJ, KELT-20 b. From the PEPSI line-by-line analysis, we obtain a representative global blueshifted wind speed of −2.55 ± 0.99 km s⁻¹, which is consistent with the previous literature value of −2.8 ± 0.8 km s⁻¹ (also traced by Fe II) in Casasayas-Barris et al. (2020). Cross correlation of the PEPSI 20190504 data set as well as the HARPS-N 20170816, 20180712, and 20180719 data sets also yields consistent results as demonstrated in the right panel of Figure 2. The lack of supersonic winds or wind variability from our analysis of Fe II absorption in KELT-20 b’s atmosphere highlights the exceptional nature of atmospheric dynamics on KELT-9 b.

We note that day-to-nightside wind measurements of KELT-20 b are significantly less sensitive to midtransit timing than KELT-9 b. From our Fe II line-by-line analysis of the PEPSI data set, we measure KELT-20 b’s orbital velocity to be 168.8±21.0 km s⁻¹; this is consistent with the measurement given in Casasayas-Barris et al. (2020), which reports Kp = 174.4 ± 14.0 as traced by Fe II lines. Consequently, due to KELT-20 b’s slower orbital velocity and larger orbital period, even an offset in the midtransit time by 10 minutes would only correspond to a 2.1 km s⁻¹ shift in the recovered day-to-nightside wind velocity. Furthermore, a revised midtransit timing would not induce variability in wind measurements across epochs (assuming the orbital period from literature is robust).

Figure 4 displays representative measurements of day-to-nightside winds for KELT-9 b and KELT-20 b over time. This
The in-transit variability of the atmospheric absorption signature seen in the PEPSI 2018 data is consistent with a picture of nightside condensation of Fe II on KELT-9 b as seen with Fe I on WASP-76 b (Ehrenreich et al. 2020; Kesseli & Snellen 2021). Over the course of a tidally-locked planet’s transit, more of the dayside is visible on the leading limb during the first half and on the trailing limb during the second half (see Figure 3 in Ehrenreich et al. 2020). Assuming the same physical picture as presented in Ehrenreich et al. (2020): (1) Fe II condenses out on the nightside and (2) more Fe II is present in the gaseous phase at the evening side than the morning side due to a longitudinal offset of the hotspot toward the evening terminator. Invoking this picture of a chemical gradient across the planet implies stronger absorption during the second half of the transit (as empirically observed) when more dayside near the evening terminator of the planet is exposed to the observer. Alternatively Savel et al. (2022) has shown that rather than iron rainout, the asymmetric Fe absorption in WASP-76 b is better explained by Al2O3, Fe, or Mg2SiO4 clouds on the cooler leading limb, which could also explain the stronger Fe II absorption we observe in the second half of KELT-9 b’s transit. Wardenier et al. (2021) also reproduces the feature with a temperature asymmetry between the leading and trailing limbs of the planet without invoking iron condensation. Stronger absorption during the second half of the transit is not quantitatively evident in the PEPSI 2019 data.

4.5. Expectations from GCMs

The magnitude and potential variability of day-to-nightside winds on KELT-9 b provide critical empirical context for general circulation models of UHJ atmospheres. Observational measurements of day-to-nightside winds provide constraints on the drag time constant of horizontal atmospheric circulation. Currently HJ GCMs predict winds between ~1–4 km s^{-1} and an amplitude of variability of the order of ~2 km s^{-1} at most (if at all) over weekly timescales (Komacek & Showman 2020; Showman et al. 2020). Our measurement may be significantly higher than theory in part because UHJs (especially KELT-9 b) can have a stronger day–night temperature contrast than standard HJs which drives faster winds; UHJ GCMs typically do not explicitly state wind speeds due to additional unknowns from second-order effects. Additionally, these models typically do not investigate the higher altitudes of the atmosphere probed by high-resolution transmission spectroscopy and wind speeds generally increase with altitude. Our empirical work motivates future theoretical work in this extreme regime.

Modeling the UHJ regime is a greater challenge than HJ GCMs for several reasons. First, the opacity of species at the extreme P–T conditions of UHJ atmospheres is difficult to quantify, both empirically and theoretically. Furthermore, chemistry plays a larger role in heat transport across UHJs as, on the dayside, they satisfy the conditions for molecular dissociation, most notably the dissociation of the dominant species, molecular hydrogen. The current picture of UHJ chemistry predicts cooling from hydrogen dissociation on the dayside and heating from hydrogen recombination on the nightside. As a result, models that include molecular dissociation yield a weaker temperature contrast and consequently weaker day-to-nightside winds than models without it (Tan & Komacek 2019; Roth et al. 2021). This additional mechanism is a computationally intensive feature exclusive to UHJ GCMs.

The greatest challenge to UHJ atmospheric circulation theory is incorporating magnetism in a self-consistent fashion.
Purely hydrodynamic models parameterize magnetic effects as a drag term (because winds that cross magnetic field lines are dampened or potentially even fully disrupted), which may not produce accurate atmospheric circulation patterns (Rauscher & Menou 2013; Komacek & Showman 2016; Tan & Komacek 2019). On the other end of the spectrum, current magnetohydrodynamical circulation models (Rogers & Komacek 2014; Rogers & McElwaine 2017) do not include a radiative transfer scheme that would allow these models to be compared with observations. They also adopt the anelastic approximation, which assumes small vertical density and temperature variations and thus underpredicts wind velocities on HJs. Beltz et al. (2021b) strikes a balance between both methodologies and adopts a spatially varying magnetic drag prescription to account for the temperature dependence and directionality of magnetic drag. However, this scheme assumes a static magnetic field and thus does not account for its evolution due to circulation in a fully self-consistent manner the way a MHD simulation would.

No UHJ GCM to date fully captures all the physical mechanisms at play. The large day–night temperature contrast on UHJs is expected to drive winds stronger than those on HJs, but the addition of both molecular dissociation and magnetic drag in UHJs are anticipated to weaken wind velocities; this could be in tension with the rapid, transonic to supersonic wind speeds we have presented. However, magnetic drag may not affect day-to-nightside winds propagated across the poles of a UHJ as strongly as equatorial jets due to the directionality of Lorentz forces (Beltz et al. 2021b). Preliminary efforts modeling the hot upper atmospheres of UHJs, the extreme P–T regime we probe with high-resolution transmission spectroscopy, show that this holds even at the ~0.1 mbar level even though the effects of magnetism grow stronger with temperature.

An added complication for KELT-9 b is that it is on a near-polar orbit around a rapidly rotating oblate star. Thus it experiences variable heating over the course of its orbit as it passes a more intense radiation environment at the poles of the star than at the equator. This could drive the observed variability in wind dynamics in addition to the standard gyres and vortices predicted by GCMs (Fromang et al. 2016; Tan & Komacek 2019). MHD simulations also predict variability of winds, especially of zonal winds in the hottest HJs, which can entirely reverse from eastward to westward (Rogers & Komacek 2014; Hindle et al. 2021). Our measured scale of variability motivates further exploration of these models and their predictions for the day-to-nightside winds typically observed with high-resolution transmission spectroscopy in addition to the zonal winds commonly studied by theorists.

5. Conclusion

We revisit the atmospheric dynamics of KELT-9 b with a revised ephemeris and a new high-resolution transmission spectroscopy data set from the PEPSI spectrograph on the LBT. Contrary to previous literature (Yan & Henning 2018; Cauley et al. 2019; Hoeijmakers et al. 2019; Yan et al. 2019), we detect significant ~4–10 km s^{-1} day-to-nightside winds as traced by line-by-line analysis as well as cross correlation of Fe II lines (Section 3). We show that the velocity shift due to the planet’s orbital motion depending on the choice of midtransit timing accounts for the disagreement with previous studies of the data sets explored in this work (Section 4). Our work motivates future multiepoch observations and analysis of UHJ atmospheric dynamics. The magnitude and variability of winds we observe pose new challenges for GCMs of UHJs, which require further theoretical exploration of second-order mechanisms, such as magnetic drag and H2 dissociation at the extreme P–T regime probed in this work.

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Software: scipy (Virtanen et al. 2020), petitRADTRANS (Mollière et al. 2019), SME (Valenti & Piskunov 1996, 2012), Time Utilities (Eastman 2012), emcee (Foreman-Mackey et al. 2013), george (Ambikasaran et al. 2015), EXOFASTv2 (Eastman et al. 2019).

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