The High-resolution Transmission Spectrum of HD 189733b Interpreted with Atmospheric Doppler Shifts from Three-dimensional General Circulation Models

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Abstract

The signature of wind patterns caused by the interplay of rotation and energy redistribution in hot Jupiters is detectable at high spectral resolution, yet no direct comparison has been attempted between predictions from general circulation models (GCMs) and observed high-resolution spectra. We present the first such comparison on near-infrared transmission spectra of the hot Jupiter HD 189733b. Exploring 12 rotation rates and two chemical regimes, we have created model spectra from 3D GCMs and cross-correlated them with the observed spectra. Comparing our models against those of HD 189733b, we obtain three key results: (1) we confirm CO and H2O in the planet’s atmosphere at a detection significance of 8.2σ; (2) we recover the signature of day-to-night winds with speeds of several km s−1 at pressures of several millibars; and (3) we constrain the rotation period of the planet to between 1.2 and 4.69 days (synchronous rotation (2.2 days) remains consistent with existing observations). Our results do not suffer from the shortcomings of 1D models as cross-correlation templates—these models mainly tend to overconstrain the slower rotation rates and show evidence for anomalous blueshifts. Our 3D models instead match the observed line-of-sight velocity of this planet by self-consistently including the effects of high-altitude day-to-night winds. Overall, we find a high degree of consistency between observations of HD 189733b and our GCM-based spectra, implying that the physics and chemistry are adequately described in current 3D forward models for the purpose of interpreting observations at high spectral resolution.

Key words: hydrodynamics – planets and satellites: atmospheres – planets and satellites: gaseous planets – radiative transfer

1. Introduction

Within the last decade, the characterization of exoplanet atmospheres has been significantly enhanced by the development of ground-based measurements using high-resolution spectroscopy (HRS, R ∼ 25,000–100,000). This powerful tool separates the planet and stellar spectra via the Doppler shift induced by the planet’s orbital motion (for close-in planets) or through spatial isolation enabled by high-contrast imaging (for wide-orbit planets); see Birkby (2018) for a recent review. In addition to enabling chemical and physical characterization of exoplanet atmospheres, those measurements at the highest resolution (R ∼ 100,000) are also sensitive to distortions in the planetary lines due to high-speed winds and/or global rotation (Miller-Ricci Kempton & Rauscher 2012; Showman et al. 2013; Kempton et al. 2014; Rauscher & Kempton 2014; Zhang et al. 2017). In the very first demonstration of the HRS method, Snellen et al. (2010) marginally detected an overall blueshift of −2 ± 1 km s−1 in the Very Large Telescope (VLT)/CRIRES transmission spectrum of the hot Jupiter HD 209458b, which was tentatively interpreted as due to high-altitude winds flowing across the planet terminator, from day to night. A few years later, line broadening in VLT/CRIRES spectra of wide-orbit companions was used to infer the fast rotational velocity (vrot = 25 ± 3 km s−1) of β Pictoris b (Snellen et al. 2014) and the much slower rotation (vrot = 5 ± 1 km s−1) of GQ Lupi b (Schwarz et al. 2016).

The close-in hot Jupiters are expected to have been tidally locked into synchronous rotation, meaning that the rotation and orbital periods are equal, with characteristic values of a few days. This corresponds to expected rotational velocities of a few km s−1, which is the same order of magnitude as our expectations for wind speeds on these planets (e.g., Showman & Guillot 2002). Beyond the tentative wind detection reported in Snellen et al. (2010), Louden & Wheatley (2015) studied the transmission spectrum of another hot Jupiter (HD 189733b) and attempted to model the radial velocities of the leading and trailing parts of the planet terminator separately. They detected an overall blueshift of −1.9±0.7 km s−1 and a significant velocity difference between the trailing and leading limbs. Under the hypothesis of rigid-body rotation, the latter was interpreted as indicative of equatorial wind speeds exceeding the pure rotational regime. Atmospheric motion of this planet was also independently detected in the infrared by Brogi et al. (2016) via VLT/CRIRES observations. The strong H2O + CO absorption (7.6σ) was found to be broadened significantly and well modeled with a global blueshift of −1.7±1.2 km s−1 and a rotational velocity of the planet compatible with synchronous rotation, while rotational periods shorter than one day were confidently (>3σ) excluded. These two studies apply a very different parameterization of the velocity field of the planet terminator; however, they both draw conclusions about planetary winds by interpreting measured radial velocities.
under the simplified hypothesis of rigid rotation. Given their exploratory nature, there is no attempt at modeling the interplay between rotation and development of large-scale atmospheric dynamics from first principles (e.g., by solving the relevant physical equations).

One key aspect of the HRS method is that it extracts the planetary signal via cross correlation of the data with atmospheric models, with the strength of the cross-correlation function (CCF) indicating the degree of match between model and data. All previous inferences on planetary winds and rotation were obtained by cross-correlating data with spectra from one-dimensional models, with the planetary lines allowed to broaden and/or shift based on some simple parameters (e.g., a simple Doppler shift for day-to-night winds and/or Doppler broadening from solid-body rotational velocities). However, treating these shifts and broadenings as effects that can be independently parameterized oversimplifies the complex physical reality of the atmosphere, where the planet’s wind pattern is fundamentally shaped by the planet’s rotation rate; the Coriolis force is one of the main balancing forces in global atmospheric dynamics. The planet’s true atmospheric Doppler signature will be from a complex combination of the multidimensional wind field and global rotation rate.

For the first time, we present an analysis of high-resolution data in which we use modeled spectra for the cross-correlation, where the spectra come from the results of a suite of three-dimensional general circulation models (GCMs), directly predicting the atmospheric velocity field for different rotation rates. We successfully use these template spectra to constrain winds and rotation of the planet HD 189733b, reanalyzing the VLT/CRiRES high-resolution transmission spectra presented in Brogi et al. (2016).

In Section 2 we describe the setup of the GCM used to predict the three-dimensional atmospheric structure and the radiative transfer model used to calculate transmission spectra with Doppler shifts and broadenings. We then present the results from each modeling component in Sections 3.1 and 3.2. In Section 4 we then describe the observations of HD 189733b that are used in our analysis, cross-correlating the data with models in Section 5. Finally, we discuss our results and summarize the most salient points in Section 6.

### 2. Computational Modeling Methods

In this study we use a GCM that solves a standard set of simplified fluid dynamics and radiative transfer equations to simulate the three-dimensional atmospheric temperature and wind structure for the hot Jupiter HD 189733b. Specifically, we use the GCM from Rauscher & Menou (2012), which solves the primitive equations of meteorology and uses two-stream double-gray radiative transfer. We calculate a set of 12 models with rotation periods ranging from 1.08 to 18.1 days, including one at the synchronous rotation period of 2.22 days (see Table 1). This is a significant expansion of our initial study of three rotation cases (two non-synchronous and the synchronous case) of HD 189733b (Rauscher & Kempton 2014), and we have also updated the planet’s radius and gravity, based on recent interferometric observations that better measure the star’s radius (Boyajian et al. 2014). The system parameters used are shown in Table 2. As in Rauscher & Kempton (2014), we use 45 vertical levels, evenly spaced in log pressure from 100 bar to 10 microbar and a horizontal resolution of T31, corresponding to ~4° in latitude and longitude, which we showed as sufficient to resolve the atmospheric flow. The resolution element is much smaller than the Rossby deformation radius of even our most quickly rotating model. We initialize each model from rest (zero winds) and run for 2000 planet orbits, by which point all of the higher (observable) levels of the atmosphere reach a steady state.

The output of the GCM is then post-processed by a radiative transfer code to calculate the wavelength-dependent attenuation of stellar light through the planetary atmosphere. This radiative transfer code is based on the 1D model originally presented in Miller-Ricci et al. (2009), which was later made publicly available as the Exo-Transmit package (Kempton et al. 2017). The proprietary version of Exo-Transmit used in this study (see Miller-Ricci Kempton & Rauscher 2012) further accounts for the local temperature, pressure, composition, and line-of-sight wind speed within each grid cell of the 3D model to compute the gas opacity, rather than assuming a radially isotropic $T$–$P$ profile. As input into the radiative transfer code, the pressure-based vertical grid from the GCM is interpolated onto one that is spaced equally in altitude, which allows us to more easily strike straight-line rays through the atmosphere. Note that this formalism works well for the upper atmosphere (pressures less than 1 mbar) that we are mainly probing, where refraction should have a negligible impact on hot Jupiter atmospheres (e.g., Bétrémieux & Kaltenegger 2014). We further neglect the effects of aerosols, which are not included in our current model. Over the very limited wavelength range of our current comparison of model to observations, aerosols should act as gray absorbers, which would primarily impact the perceived continuum level of the transmission spectra. As the continuum information is lost in the observational data reduction process, we conclude that our current analysis is not sensitive to the presence of aerosols and we are therefore justified in neglecting their effects. The radiative transfer equation is then solved for the case of pure absorption:

$$I(\lambda) = I_0 e^{-\tau(\lambda)}$$

where $I_0$ is the incident stellar intensity and $\tau$ is the line-of-sight “slant” optical depth as a function of wavelength. The latter is
calculated according to
\[ \tau(\lambda) = \int \kappa(\lambda) ds. \]  
\(2\)

In Equation (2), \(\kappa\) is the local gas opacity in a given grid cell of the 3D atmosphere, and \(ds\) is the line-of-sight path length traveled through that grid cell. The optical depth \(\tau\) is calculated along a total of \(2 \times \text{NALT} \times \text{NLAT}\) individual rays, where NALT is the number of vertical levels and NLAT is the number of latitude grid cells in the 3D model. The factor of two comes from integrating the light propagating through the planetary atmosphere on both the eastern and western limbs.

Doppler shifts resulting from winds and rotation need to be accounted for because these effects are often larger than both the natural width of individual molecular lines and the resolution elements of a high-resolution spectrograph (e.g., CRIRES with \(R \sim 100,000\)). For this reason, the local opacity in each grid cell is Doppler-shifted according to the line-of-sight gas velocity \(v_{\text{LOS}}\) given by
\[ v_{\text{LOS}} = -(u \sin \theta + v \cos \theta \sin \phi + (R_p + z) \Omega \sin \theta). \]  
\(3\)

The first part of the equation calculates the line-of-sight velocities caused by the winds (\(u\) and \(v\) being the east–west and north–south components of the wind respectively, at latitude \(\phi\) and longitude \(\theta\)) while the second calculates the line-of-sight velocities caused by the planet’s rotation \(R_p\), being the planet’s radius at 1 bar, \(z\) being an altitude at a given pressure level, and \(\Omega\) the planet’s bulk rotation rate). We therefore self-consistently account for the effects of planetary winds and rotation on the high-resolution transmission spectra. The Doppler effects of orbital motion, which will equally impact each grid cell of the 3D model, are accounted for in the data analysis process, described separately.

We calculate the transmission spectrum for a wavelength range of 2285–2347 nm and a spectral resolving power \(R = 2.5 \times 10^5\), which is then convolved to a lower resolution of \(R = 1.0 \times 10^5\) for direct comparison to data described in Section 4. The dominant feature within this particular wavelength range (corresponding to the wavelength range of the CRIRES observations we will analyze using these models) is the strong, separated “comb” of CO lines, with \(\text{H}_2\text{O}\) and \(\text{CH}_4\) providing the next strongest sources of opacity (Miller-Ricci Kempton & Rauscher 2012). We note that we updated our \(\text{H}_2\text{O}\) opacity line list in this work from the sources listed in Table 2 of Lupu et al. (2014) to HITEMP (Rothman et al. 2010), which we found was necessary to generate a positive cross-correlation signal for this molecule.

In our previous studies (Miller-Ricci Kempton & Rauscher 2012; Rauscher & Kempton 2014), we computed idealized models in which the stellar disk was assumed to have uniform intensity. However, in this work we are comparing our models to observations obtained at various times during transit, and it is therefore necessary to include the effects of stellar limb darkening. We employ the quadratic limb darkening model described in Brogi et al. (2016):

\[ I(\mu) = 1 - u_1(1 - \mu) - u_2(1 - \mu)^2 \]  
\(4\)

where \(\mu\) is the cosine of the angle between the line of sight and the normal to the stellar surface, and the limb darkening parameters \(u_1\) and \(u_2\) for HD 189733 are 0.077 and 0.311 respectively (Claret & Bloemen 2011). Using Equation (4), we generate a pixilated model “star” where each pixel has an intensity between 0 and 1. To generate transmission spectra from the GCM output, we determine which stellar pixel illuminates each grid cell of the planetary atmosphere at the orbital phase of a given observation. The incoming stellar intensity is then multiplied by the appropriate limb-darkened scaling factor, such that \(I_0 = I(\mu)\).

For each of the rotation models, at each point in the observed transit, we then calculate the observed flux by first subtracting the flux blocked by the planet and the atmosphere from the total stellar flux then adding back in the flux that passes through the atmosphere. The total integrated flux through the atmosphere is the sum of the intensities of each line-of-sight ray, multiplied by the 2D projected solid angle of its associated atmospheric grid cell.

We have modeled our transmission spectra at 39 different consecutive times in transit that correspond to the observations described in Section 4, and explored the different effects the planet’s winds and rotation have on the spectra by turning on and off different physical aspects, creating wind-only, rotation-only, and combined-effects models. Additionally, we have modeled these spectra under two different chemical regimes. The first is a regime of constant volume mixing ratio (VMR), in which molecular hydrogen, water, and carbon monoxide have constant abundances throughout the atmosphere at 99.8%, 0.1%, and 0.1%, respectively. These values were selected to match the best-fit values from the previous analysis of these
data in Brogi et al. (2016), and such fixed VMRs could be physically representative of a planet with quenched chemical abundances, in which atmospheric dynamics distribute molecular species faster than chemical reaction rates can return the gas mixture to thermochemical equilibrium (e.g., Moses et al. 2011; Venot et al. 2012, 2015; Drummond et al. 2018). The second case considered is that of local chemical equilibrium (LCE), which is a reasonable first-order approximation for hot planets such as HD 189733b.

3. Model Results

3.1. GCM Results

The 12 models of HD 189733b we simulated, with the range of rotation rates shown in Table 1, reproduce the circulation patterns we have come to expect from previous work. The model of HD 189733b with synchronous rotation shows the standard hot Jupiter circulation pattern (Showman & Polvani 2011; Perez-Becker & Showman 2013; Komacek & Showman 2016); the development of an eastward jet along the equator, which extends throughout most of the atmosphere. High in the atmosphere, for pressures less than \(\sim 0.1 \text{ mbar}\), the eastward equatorial flow is accompanied by a significant direct substellar-to-antistellar flow. The top panel of Figure 1 shows a map of the temperature and flow pattern in this regime, which is the pressure range preferentially probed by transmission spectroscopy. The bottom panel of Figure 1 shows the temperature and wind pattern near the planet’s infrared photosphere, where the equatorial jet is able to advect the hottest region of the planet eastward of the substellar point before it can cool efficiently. This is the atmospheric structure that influences observations of the planet in emission. The maps of the upper atmosphere and infrared photosphere for all models can be found in Appendix A.

When we compare the synchronous case to models with faster and slower rotation rates, we also find the trends that we expect. The faster the rotation, the stronger the role of the Coriolis force in constraining the wind patterns, and so we see thinner jets and more of them, while in the more slowly rotating models (up through the model with \(P_{\text{rot}} = 4.69 \text{ days}\)), the equatorial jet becomes wider in latitudinal extent. High in the atmosphere there is a more complex interaction between the jet pattern and the day-to-night flow, but the same general trends hold true. As the jets get narrower their wind speed also decreases (see Table 1). This can be simply understood as horizontal shear limiting the latitudinal gradient in wind speed; for the same wind speed, the thinner jets would produce much stronger horizontal shear than the wider ones. These trends match those originally seen in the non-synchronous hot Jupiter models of Showman et al. (2009) and Kataria et al. (2013). An exception to this gentle trend in jet width and speed is seen for the two most slowly rotating models, where the circulation pattern is disrupted and becomes dominated by westward flow near the IR photosphere. This change in circulation regime for very slow rotators was originally discovered by Rauscher & Kempton (2014) and has been dynamically analyzed by Penn & Vallis (2017). Figure 2 shows average profiles of the planet’s east–west winds throughout the atmosphere, for the slowest, synchronous, and fastest rotation models; these plots for all 12 models can be found in Appendix B.

The disrupted circulation pattern of the two most slowly rotating models has an immediate observable implication: the westward flow forces the hottest region of the atmosphere to be at—or even westward of—the substellar point. In Figure 3 we show simulated flux curves of planet emission as a function of orbital phase, and the slowest rotating models are notably different in when the peak flux occurs. The planet HD 189733b has been observed in thermal emission at multiple wavelengths, and those data all show a peak in flux that occurs before secondary eclipse (Knutson et al. 2012, which corresponds to an orbital phase of 0.5 and is when the substellar point on the planet is facing directly toward the observer. For all of our models with rotation faster than \(P_{\text{rot}} = 7.45 \text{ days}\), the hot-spot is shifted to the east of the substellar point, resulting in phase curves that agree with observations, but the two most slowly rotating models are inconsistent with the data. Although phase curves are useful in ruling out these slower cases, the shapes of the remaining phase curves are subject to degeneracies (e.g., Showman et al. 2009), making it difficult to constrain the rotation rate. Thus, HRS that can detect the Doppler signatures of winds and rotation is a more direct means of determining the rotation rate of a planet.
While the bulk rotation of the planet will induce a broadening of transmission line profiles, the atmospheric dynamics will also contribute to the width and shift of lines, depending on the particular pattern of winds in the region of the atmosphere probed by these observations. The absorption lines we measure in this wavelength range should originate from pressures between roughly 0.01 and 1 mbar (Miller-Ricci Kempton & Rauscher 2012). At these pressure levels the flow is a combination of a day-to-night component and the eastward equatorial jet, for the synchronously rotating model (see Figure 1). The upper atmosphere flow patterns for all models, shown in Appendix A, demonstrate that the particular details of the wind structure are strongly influenced by the planet’s rotation rate. As Table 1 reports, the wind speeds can exceed the planet’s bulk rotational speed, meaning that the complex velocity pattern due to the atmospheric circulation plays an integral role in shaping the observed spectra.

Figure 4 helps to visualize the relative contributions of the wind and rotational velocity structures to the line-of-sight Doppler shifts probed in transmission. We show the local line-of-sight velocities, for a cross section of the atmosphere through the planet’s terminator, with the planet oriented as during transit (and with the radial scale of the upper atmosphere enlarged to show spatial detail). The path that a light ray takes in transmission through the planet’s atmosphere crosses multiple longitude and altitude locations, so the full three-dimensional calculation is needed to fully capture the Doppler shifts in detail, but the terminator cross section is a good first approximation. In particular, this shows that the high-altitude wind pattern in the synchronous model has equatorial eastward flow at similar speeds to the day-to-night flow over the poles; the former component is roughly doubled by the contribution of the rotational velocities, while the flow near the poles is minimally affected.

In Appendix C we show the line-of-sight velocity cross sections for all 12 models, with the combined wind and rotational components. As indicated by Table 1, we see from these patterns that the rotational velocities should dominate the Doppler signal in the most quickly rotating models, while the wind pattern is the main contributor for the more slowly rotating models. While the prevalent equatorial eastward jet contributes to Doppler broadening in an additive way with the rotational field, these plots show that the substellar-to-antistellar flow component should preferentially induce a blueshifted signal, especially for latitudes nearer to the poles. We may also expect that the spatial structure of the line-of-sight velocities may lead to anomalous Doppler shifts when the planet is at or near the edge of the limb-darkened star, because some parts of the atmosphere will be preferentially illuminated.
3.2. Transmission Spectrum Results

Prior to comparing our models directly to the observed data, we first perform “model-on-model” cross correlations of our model spectra against a narrow rest-frame template (no Doppler shifts applied from winds or rotation) to separately assess the effects of winds and rotation on each of our calculated spectra. The rest-frame template used for this entire analysis is a model produced at the center of transit (impact parameter of zero). Later, when comparing the models to data in Section 5, we will use the full 3D consistent model spectra as the cross-correlation templates. We perform the model-on-model analysis for five points in HD 189733b’s observed orbit (early ingress, mid ingress, central transit, mid egress, and late egress), as shown in Figure 5 for the tidally synchronous case. The spectra at ingress and egress differ from that at central transit in that only a portion of the planet is in front of the host star, which can substantially bias the cross-correlation signal relative to what would be expected during transit “totality,” when the planet is fully in front of its star. For example, during ingress the rotationally receding limb of the planet occults the star, which brings about an excess redshift in the net cross-correlation velocity.

The cross-correlation process has greatest sensitivity to the strongest absorption features, which are optically thick at pressures \( \lesssim 1 \text{ mbar} \). As a result, the transmission spectrum primarily probes the velocity field in the upper atmosphere, which is dominated by day-to-night winds. This is apparent in the CCFs, which tend to be strongly peaked at blueshifted velocities for each of the center-of-transit models (Figure 13). Separately analyzing the contributions due to winds and the planet’s rotation, we find net blueshifts due to winds in each of the models at the level of \( \sim 1-2 \text{ km s}^{-1} \), regardless of rotation rate. The equatorial jet also contributes to the Doppler shift signature of the winds. This provides a broadening component to the shape of the CCF resulting from the approaching and receding components of the jet across opposing limbs. The planet’s rotation provides an additional broadening component to the CCF for cases where the rotational velocities are larger than the wind velocity dispersion. This occurs for all of the models with \( P_{\text{rot}} > 2.6 \text{ days} \). For the slowest rotating models, the velocity dispersion from winds exceeds that of the rotational motion, and the width of the CCFs is set by the winds alone. A key implication is that signatures of planetary rotation are not expected to be identifiable from cross-correlation analysis alone if the planet is rotating sub-synchronously, because of the dominant effects of atmospheric winds.

One might expect the effects of rotational broadening to be symmetric about a velocity shift of zero, but from Figure 13 we see that the faster rotating models produce CCFs that are broader, but also more asymmetric toward blueshifted velocities. This comes about for two reasons. First, the blueshifted limb of the planet is also the hotter one (because the hot-spot leads ahead of the substellar point), which causes the approaching limb to also be more inflated. In contrast, the redshifted limb is cooler and less inflated, and therefore occults a geometrically smaller portion of the host star. Second, the cooler redshifted limb also has a lower abundance of CO (and a correspondingly greater abundance of CH₄), which leads to a weaker cross-correlation signal coming from that side of the planet.
We note that these CCFs obtained from noiseless model spectra cannot be compared directly to CCFs obtained by cross-correlating against observed data. The analysis that we apply to observations also produces distortions in the planet spectrum, which could potentially mimic signatures of atmospheric circulation or be partially confused with them. Consequently, in the next section we explain how we process real observations to correct for these effects of our data analysis technique.

4. Observations

The data utilized in this study are described in detail in Brogi et al. (2016). They consist of a sequence of 45 high-resolution, near-infrared spectra observed at the CRIRES spectrograph (Kaeufl et al. 2004) on 2012 July 30, as part of DDT program 289.C-5030. The spectrograph, now decommissioned, was mounted at the ESO Very Large Telescope UT1 in Chile and operated at a resolution of $R \approx 100,000$ with a 0.2 wide slit, covering the range 2287.5–2345.4 nm in the configuration adopted here.

The observations were carried out by nodding along the slit via an ABBA pattern for accurate subtraction of thermal background and emission lines in the Earth’s atmosphere. With an exposure time of 60 s per nodding position, we obtained 90 spectra, or 45 couples of AB or BA pairs. These are combined through the standard CRIRES pipeline and the corresponding 45 one-dimensional spectra extracted. We obtain an average signal-to-noise ratio (S/N) of 225 per pixel (1 pixel corresponds to approximately 1.5 km s$^{-1}$ in velocity space) in spectral regions free from absorption lines.

The subsequent calibration of the data is described in Brogi et al. (2016) and consists in realigning all the spectra to a common wavelength scale, which is chosen to be that of the absorption lines in the Earth’s atmosphere (telluric absorption). In this way, telluric lines always fall on the same spectral channel, and they also provide an accurate wavelength calibration for our spectra, with typical precision of 50–75 m s$^{-1}$ per line.

We depart from Brogi et al. (2016) for the correction of the stellar spectrum. Stellar CO lines are distorted by the transit of the planet producing the well-known Rossiter–McLaughlin (R–M) effect. Although the effect on the centroid of stellar lines is of the order of tens of m s$^{-1}$, once the average line profile is removed by our analysis the actual change in radial velocity in the residual stellar component spans $\pm v \sin(i_*)$ during transit, which is $\pm 3.3$ km s$^{-1}$ in the case of HD 189733. The amplitude of these residuals is 0.5%–1.0%, which is sufficient to outshine the atmospheric signature of HD 189733b. We therefore proceed to model the R–M effect as in Brogi et al. (2016), but using as input a spatially resolved, 3D stellar model matching
the properties of the star (5000 K, log(g) = 4.5, [Fe]/[H] = −0.03). This was produced using the state-of-the-art realistic three-dimensional radiative hydrodynamical (RHD) simulations of stellar convection carried out with the Stagger code (Nordlund et al. 2009). The grid of RHD simulations covers a large part of the H-R diagram, including the evolutionary phases from the main sequence over the turnaround to the red-giant branch for low-mass stars (Magic et al. 2013). The simulation used in this work has been employed to compute synthetic spectra in the same spectral range as the observations with the multidimensional pure-LTE radiative transfer code Optim3D (Chiavassa et al. 2009, 2018). The code takes into account the Doppler shifts occurring due to convective motions and solves monochromatically for the emerging intensity, including extensive atomic and molecular continuum and line opacity data from UV to far-IR.

At the resolution of CRIRES, it is possible to isolate a set of stellar CO lines far from telluric absorption and visually verify that the chosen stellar parameters are appropriate, i.e., the modeled spectral lines have the correct depth and shape. Using a model for the stellar spectrum is a major improvement from our previous study, which instead relied on parameterizing an average stellar line profile through micro- and macroturbulence, and was inadequate to reproduce the complicated velocity fields in the convective envelope of the star.

We could not properly correct the spectra falling on detector 3 of CRIRES with the above analysis. Given the high density of both stellar and telluric lines in that spectral region, it is likely that our algorithm to reconstruct the instrument profile through singular value decomposition fails, leading to an imperfect correction of stellar lines. Since detector 4 is also excluded due to a well documented problem with the differential gain of odd and even columns, we are left with only half of the spectral range of CRIRES for this study (detectors 1 and 2, spanning 2287.5–2316.0 nm).

After dividing out the model stellar spectrum, telluric lines were removed and the residual spectra cross-correlated as in Brogi et al. (2016) to combine the signal of all the individual absorption lines in the planet transmission spectrum into one CCF.

### 5. Data Cross Correlation

Before comparing the GCM models to these data, we repeat the analysis of Brogi et al. (2016). This is necessary to verify consistency, since our procedure to correct for the stellar spectrum has changed. The only other difference from the previous analysis is that we increase the resolution in the semi-amplitude of the planet’s orbital radial velocity ($K_p$), and we use a new set of values for the planet’s rotational equatorial velocity ($V_{eq}$) consistent with the input parameters for this work (Table 1, right column). In this analysis, the data are always cross-correlated with a narrow template for the planet transmission spectrum, which is a model not including the velocity field due to winds and rotation (this is the center-transit model already described in Section 3.2 and utilized to obtain the theoretical CCF of our models). Since the cross-correlation operator is similar to a convolution (i.e., it broadens the planet line profile), this choice ensures that we apply a consistent level of broadening throughout the analysis. In order to evaluate the goodness of fit of models with varying circulation patterns, we need to estimate how the true planet line profile is broadened by cross correlation and possibly altered by our data analysis. Following Brogi et al. (2016), we inject each model in the data immediately after wavelength calibration and pass the injected signals through the pipeline. To ensure that the injection does not sensibly alter the analysis, models are scaled down to line contrast ratios of at most $10^{-4}$ compared to the stellar continuum. The CCF of the injected signal (CCF$_{inj}$) will contain the model, the real signal, and noise. The CCF of unaltered data (CCF$_{real}$) will instead only contain real signal and noise. Since the noise remains constant due to the very small injection, we can apply the linearity of the cross-correlation operator and obtain the CCF of the injected model via

$$CCF_{mod} = CCF_{inj} - CCF_{real}. \quad (5)$$

where CCF$_{mod}$ incorporates the same broadening and distortions as the real signal. It can thus be compared to the CCF of the real signal through chi-square analysis. As outlined in detail in Brogi et al. (2016), we assign a significance to each model based on how much more favorable its CCF is compared to a straight line. The latter indicates zero signal by definition,
which occurs when the sample of cross-correlation values is consistent with a Gaussian distribution.

Figure 6 shows the confidence intervals for $K_P$, $V_{eq}$, and the planet’s rest-frame velocity ($V_{rest}$). Despite using only 2/3 of the data of Brogi et al. (2016), we obtain a stronger detection of the combined absorption of CO and H$_2$O at a significance of 8.6σ. This indicates that by improving the correction of the stellar spectrum we are also preserving a larger fraction of the planet signal, especially the CO spectrum. Qualitatively we confirm that our measurements are compatible with synchronous rotation, but the stronger detection and better cleaning of stellar residuals allow us to improve the confidence intervals in all three parameters. We measure $V_{eq} = 3.4^{+1.0}_{-0.9}$ km s$^{-1}$ (previously $V_{eq} = 3.4^{+1.3}_{-1.1}$ km s$^{-1}$), and rotation is now favored over models without rotation at 2σ (previously 1.5σ). Rotational periods shorter than 1.2 days are now excluded at >3σ. The signal peaks at a planet rest-frame velocity of $V_{rest} = -1.4^{+0.8}_{-0.9}$ km s$^{-1}$ (previously $V_{rest} = -1.7^{+1.2}_{-1.1}$ km s$^{-1}$), which corresponds to a global blueshift in the planet CCF detected at 1.9σ. This is expected in the presence of day-to-night side winds since these are not included in the rigid-rotation model. Finally, we measure the planet’s radial-velocity semi-amplitude to be $K_P = 131^{+22}_{-14}$ km s$^{-1}$, compared to the previous value of $K_P = 194^{+48}_{-37}$ km s$^{-1}$, which is still consistent with the literature value of $K_P = 152^{+33}_{-18}$ km s$^{-1}$ computed in Brogi et al. (2016).

We now proceed to compare the models computed in this paper with the data (see Figure 7). We obtain a detection at a confidence level of 8.2σ for the models in LCE (top panels), whereas the models with VMR of 10$^{-3}$ for CO and H$_2$O deliver a detection at 7.4σ (lower panels). The middle and right panels clearly show that the planet signal retrieved with the full GCM models now peaks at zero rest-frame velocity. This is a strong indication that our 3D models correctly predict the global atmospheric circulation at the terminator, in particular the flow at relatively high altitude that produces a net blueshift. In contrast, from the left and middle panels, we note that the rotational rate of the planet becomes poorly constrained, except perhaps for very fast rotations.

Lastly, in Figure 8 we show the results from the same GCM models when the atmospheric circulation is turned off. These models hence only contain the effects of rotation. With these models we would expect the same qualitative results as for the repeated analysis of Brogi et al. (2016), except that the planet is no longer a rigid body. Not only is the significance of the detection enhanced with this last set of models (8.7σ and 8.3σ for LCE and VMR, respectively), but we also recover the sensitivity to the synchronous rotational period and exclude both fast and slow rotations. Having suppressed winds in the planet’s atmosphere, the signal is again retrieved blueshifted, as expected when the global high-altitude winds are not modeled.

### 6. Discussion and Future Prospects

We have shown that models using fully integrated physics and computed from first principles deliver cross-correlation signals as significant as those obtained with simple parameterized models, optimized through a chi-square grid search. This key result suggests that the main assumptions of these GCM
models are sound, and that the global atmospheric flow is correctly reproduced.

In particular for HD 189733b, we confirm the detection of an overall blueshift of the planet’s transmission spectrum by \(-1.4^{+0.8}_{-0.9}\) km s\(^{-1}\). More importantly, since the planet signal is retrieved at zero rest-frame velocity when cross-correlating with our GCM models, we are finally able to directly link this shift to the presence of high-altitude winds flowing from the day to the night side of the planet, confirming one of the main theoretical predictions about the main atmospheric flow in irradiated giant exoplanets.

Furthermore, the onset of strong equatorial super-rotation significantly broadens the planet line profile even for very slow rotation (low equatorial velocity \(V_{\text{rot}}\)). Consequently, it is challenging to constrain these slow rotational regimes, at least at the current spectral resolution and S/N of the observations. This demonstrates the utility, effectiveness, and need for the use of model predictions in analyzing high-resolution transmission spectra of hot Jupiters. Models neglecting the interplay between atmospheric winds and the planet’s rotation—for instance by independently retrieving rotational period and equatorial velocity—would measure much tighter but incorrect constraints on the planet’s rotational rate, because they would not account for the fact that these two parameters are physically correlated. The slowest rotational rates can, however, be constrained by adding the information from photometric phase curves. We showed that the thermal emission peak in models with the longest orbital periods occurs after secondary eclipse, which is inconsistent with pre-secondary eclipse peaks observed for not only HD 189733b, but a significant fraction of the hot Jupiters.

Conversely, we confirm the ability to constrain fast rotational rates, which again dominate the broadening of the planet line profile regardless of the additional equatorial flow. This means that in the future it will be possible to expand these observations to systems of different age and orbital separations, and test under which regime(s) synchronous rotation breaks down. Non-tidally locked giant planets, if they rotate as fast as the solar system giants, will be easily discriminated with equatorial velocities in excess of \(10\) km s\(^{-1}\). These measurements will be key to constraining how interiors of giant planets react to tides, which is still poorly known for solar system planets.

Our analysis is currently limited to two possible chemical regimes, namely LCE abundances for solar metallicity or a slight superabundance of water and carbon monoxide at VMR \(= 10^{-3}\). We see some indication that LCE models match the data more closely, with an increase in detection significance of 0.8\(\sigma\). However, we are not yet at a stage where we can explore the opacity effects of different molecular species and abundances, nor did we attempt to adjust tunable parameters in the GCM simulation, such as the numerical dissipation necessary to capture sub-grid sources of physical dissipation. Thrastarson & Cho (2011) discuss some of the nuances and uncertainties associated with numerical dissipation. Since the radiative timescales vary by orders of magnitude within the atmosphere, it is possible that the regions of lowest pressure (highest altitude) are underdamped in comparison to the rest of the atmosphere. Exploring large grids of the above
parameters is still prohibitive due to the fact that these GCMs are computationally intensive.

In addition to physically based models for planet atmospheric circulation, in this work we have also utilized physically based, three-dimensional models of the stellar spectrum. These can correctly reproduce variations in the stellar convective blueshift and optical path along the disk, allowing us to model in unprecedented detail center-to-limb variations and the R-M effect caused by the planet during transit. Correcting our spectra with such models has led to an increase of 1σ in the significance of the detected planet signal, even though we only utilized 2/3 of the data of Brogi et al. (2016). This highlights the importance of accurate and precise stellar models at high spectral resolution to maximize the scientific return of high-resolution observations of the exoplanets that orbit these stars. To that end, synergistic work between the stellar and exoplanetary communities is warranted.

In conclusion, we have shown that HRS uniquely constrains both atmospheric circulation patterns and rotation rates. In addition to the constraints coming from broadband photometry and spectrophotometry, we now have the ability to directly measure wind speeds of a few km s⁻¹ reflected in the shape of CCFs. With new and improved high-resolution spectrographs coming online in the near future and more immediate follow-up high-resolution spectroscopic studies on new survey targets (such as bright planets discovered with NASA’s Transiting Exoplanet Survey Satellite), it will be possible to implement analysis techniques such as the ones presented in this paper to characterize a homogeneous set of transiting planets around bright stars. With enough S/N and time resolution, we could potentially trace the minute differences in the terminator flow during the varying phases of a transit (Miller-Ricci Kempton & Rauscher 2012). Even for non-transiting planets, winds and rotation are expected to affect line shapes in emission spectroscopy (Zhang et al. 2017), and we aim at testing these predictions in future studies. Ultimately, the advanced characterization methods that are currently only feasible for hot Jupiters will be employable on smaller and cooler planets, with the goal of characterizing potentially habitable worlds.

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Appendix

In the following sections we include plots showing the results from each of our 12 differently rotating models. Appendix A (Figures 9 and 10) contains maps of atmospheric temperatures and winds, for the 0.1 mbar and infrared photosphere levels, equivalent to the one shown for the synchronous case in Figure 1. Appendix B (Figure 11) shows the zonal wind patterns for all models, equivalent to Figure 2 in the main text. We show the line-of-sight velocity cross sections (as in Figure 4) for all models in Appendix C (Figure 12). Finally, Appendix D (Figure 13) contains a single modeled center-of-transit CCF for each model, described in Section 3.2 and shown in Figure 5 at several points during transit for the synchronous case.
Appendix A
Maps of the Temperature and Wind Structure in the Upper Atmosphere and at the Infrared Photosphere

The maps have been shifted such that the substellar point (during transit for the non-synchronously rotating models) is at the center of the plot. The tidally synchronous case is outlined in black in both Figures 9 and 10. At the pressure level in Figure 9 (0.1 mbar) and those higher in the atmosphere, the flow is composed of a direct substellar-to-antistellar component and the equatorial jet. At the fastest rotation rates the day-to-night flow competes with multiple eastward jets, while at the slowest rotation rates the eastward equatorial jet becomes disrupted and there is even strong westward flow across the night side. In Figure 10 (130 mbar), one can see how changing the rotation rate of the planet influences the pattern of winds, disrupting the standard eastward wind direction in the slowest cases. The day–night and equator-to-pole temperature gradients also differ between the different rotation models.

Figure 9. Global temperature and wind maps of the upper atmosphere (0.1 mbar) for all 12 rotation models.
Zonal wind maps for the 12 rotation models are shown in Figure 10, with the tidally synchronous case outlined in black. Note: the color scale for these models is different than the color scale for the zonal wind maps presented in Figure 2. For the sake of uniformity, they are all on the same scale. The standard eastward equatorial jet seen in the case of synchronous rotation becomes broader and then disrupted at slower rotation rates. At faster rotation rates it narrows and additional jets form at higher latitudes.

**Appendix B**

**Zonal Wind Maps**

Zonal wind maps for the 12 rotation models are shown in Figure 10, with the tidally synchronous case outlined in black. Note: the color scale for these models is different than the color scale for the zonal wind maps presented in Figure 2. For the sake of uniformity, they are all on the same scale. The standard eastward equatorial jet seen in the case of synchronous rotation becomes broader and then disrupted at slower rotation rates. At faster rotation rates it narrows and additional jets form at higher latitudes.
Appendix C

Line-of-sight Velocity Maps

Figure 12 shows the line of sight velocity maps for all 12 rotation models, showing contributions for both winds and rotation. The pressure levels are all the same as the ones labeled in the tidally synchronous case. Even the most slowly rotating models have significant

Figure 11. The longitudinally averaged east–west (zonal) wind, as a function of latitude and pressure (the vertical coordinate) for all 12 rotational models.
red- and blueshifts at the terminator, due to the presence of strong winds blowing east around the equator. These strong winds contribute to the broadening of and additional peaks in the cross-correlation functions (shown in Figure 13). Note: the atmosphere is not to scale with the size of the planet.

Figure 12. Cross sections along the planet’s terminator, showing the line-of-sight velocities toward an observer during transit, for all 12 rotation models including the contributions from both winds and rotation.
Appendix D

Center Cross-correlation Functions

The center cross-correlation plots are shown in Figure 13 for all 12 models. Each model’s rotation-only (yellow), wind-only (blue), and combined winds and rotation (red) transmission spectra were cross-correlated with the non-moving case in order to determine the velocity contribution of each process. The black line shows the non-moving case cross-correlated with itself as a

![Cross-correlation functions at central transit for the 12 rotation models.](image)

*Figure 13. Cross-correlation functions at central transit for the 12 rotation models.*
reference point. Notably, winds are able to significantly broaden the line profiles of the most slowly rotating models, while in all models they contribute toward blueshifting the net Doppler signature.

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