Using Transmission Spectroscopy to Determine the Rotational and Atmospheric Dynamics of Hot Jupiters

I. Introduction

Of the 5000+ exoplanets (that is, planets that orbit stars other than our sun) that have been detected, most of these are what are known as “hot Jupiters.” These gaseous planets are the size of Jupiter or larger, orbiting very closely to their parent stars – closer even than Mercury orbits the sun – and generally presumed to be tidally locked, one side of the planet constantly facing the star as it orbits. Most of the exoplanets we have detected are these large hot Jupiters as a result of our observational methods and capabilities. There are two main methods for detecting exoplanets: the radial velocity method and the transit method. The former works on the principle that both the star and the exoplanet are orbiting the center of mass in the system. As the exoplanet orbits the star, it gravitationally tugs on the star, causing it to periodically “wobble” when we observe it. This wobble is measured as a periodic red- and blueshift of the starlight, and the magnitude of this affect depends on the mass of the exoplanet. The latter method measures periodic changes in starlight to detect an exoplanet. As the planet crosses through our line of sight, it will block a percentage of the starlight that reaches us that is dependent on the radius of the planet. The larger the exoplanet, the larger the drop in starlight. Thus, the exoplanets that are the easiest for us to detect are these large hot Jupiters. They make very interesting objects of study, as we do not have an example in our own solar system of such a planet, and much about their formation and structure remains mysterious. In order to try to uncover some of the mystery though, we can create models and compare their results to observations. One useful observation is that of the exoplanet’s atmospheric spectrum.
II. Background

As previously mentioned, one way to detect an exoplanet is to study the periodic change in starlight. But we can observe more than just a brightening and dimming of a star. Some of the starlight will pass through any atmosphere that is present, and when this happens, different molecules present in the atmosphere will absorb and emit light at wavelengths specific to each compound. We then can observe what is known as the transmission spectrum of the planet’s atmosphere by comparing the star’s spectrum before and during transit. The difference between the star’s spectrum before and during transit is due to the exoplanet’s atmosphere, and it can tell us many things. It can tell us about the composition of the atmosphere, but it can also tell us something about the dynamics and structure. The shape of the spectral lines arises from various sources of Doppler shift and Doppler broadening. As the planet orbits the star, it moves towards and away from us, resulting in the spectrum to be blueshifted (shifted towards shorter wavelengths) and redshifted (shifted towards longer wavelengths) respectively. But the rotation of the star, the planet, and the planet’s atmosphere will similarly cause blue- and redshifts, and all of these shifts are directly proportional to how fast each component is moving. Winds on the planet particularly will cause the spectral lines to appear broader than lines produced by an object at rest, and the amount by which those lines are broadened corresponds directly to the wind speeds. In order to learn about these dynamical components though, we need to compare observations of exoplanet atmospheric spectra to models.

III. Creating Transmission Spectra

My project this summer was to create multitudes of model spectra to be compared to observed spectra of the hot Jupiter HD 189733b in order to more precisely determine the rotation rate of the exoplanet. I developed and wrote scripts that would account for winds, planet rotation, and planet orbit (separately and simultaneously) in the shape of the transmission spectra, under two chemical composition regimes. In the first chemical regime, the only
molecules present in the atmosphere are H$_2$O and CO with .1% abundance each, and H$_2$ in 99.8% abundance. In the second regime, many different chemicals are present in abundances that result from local chemical equilibrium. The transmission spectrum model takes input from the results of a 3D General Circulation Model developed by my mentor, Prof. Emily Rauscher. This solves for a simplified version of the radiative transfer process derived from fluid dynamics equations. The result is a three-dimensional “map” of the atmosphere’s temperature, pressure, and wind speeds at different latitude, longitude, and altitude points. The transmission spectrum code then takes this information and applies the desired Doppler effects to produce the model spectra. In order for the model to be more realistic than previously, I also made it account for an effect known as stellar limb darkening. This effect is the fact that stars are brighter towards their centers than they are towards their edges, and as the spectrum one observes is dependent on the amount of light that one detects, it is important to account for this effect when producing models. One of the resulting spectra, comparing the results for different Doppler effects and including the effect of limb darkening, is shown below.

![Figure 1: Spectra due to different Doppler effects for tidally locked case, rotation period = 2.22 days. Large spectral features are due to H$_2$O.](image-url)
### IV. Conclusion

I am continuing to create transmission spectra for twelve different rotation period cases under the two aforementioned chemical regimes, at 39 different points in the planet’s transit. These will all be sent to our colleague Dr. Matteo Brogi at UC Boulder for him to compare to observed spectra of HD189733b using a cross-correlation function. In the past, he carried out a similar study using a simpler model, and the comparison between the model and the observation predicted a rotation rate that fell within a confidence interval $\Delta \sigma$ of one (see Figure 2), but we hope to narrow down that confidence interval with these new models (Brogi et al. 2015). Although it is assumed that this and other hot Jupiters are tidally locked, there have not been many – if any – direct confirmations of this.

![Figure 2: Significance of the detected transmission spectrum of HD 189733 b for the best fitting model presented in Section 5.2 and varying rotational velocities $v_{rot}$ and maximum orbital radial velocities $K_P$. Colored contours express the gain in significance $\Delta \sigma$ with respect to a straight-line fit to the CCF. Since a straight line means no detection by definition, $\Delta \sigma$ also represents the significance of the detection (see Sections 4.4 and 5.3 for details). Labeled black and white contours show the confidence intervals for the two planet parameters. Their best estimate is marked with a plus sign, while the value expected by assuming tidal locking and the value of $K_P$ from Equation 15 is indicated with a diamond.” (Brogi et al. 2015)](image)

Due to current observation limitations, we can only indirectly study exoplanets via their effect on the light of their parent stars. Even so, we can learn a lot about their dynamics by comparing those indirect observations with
models, with the ultimate goal being to conduct similar studies with terrestrial planets, looking for potential signs of life on worlds beyond our own.

V. References