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Discovering the atmospheres of hot Jupiters

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Abstract. Hot Jupiters are an extraordinary class of exoplanets, orbiting their host stars with periods of hours to a few days. Some of these objects have day-side temperatures approaching photospheric temperatures of late K-type stars. I will give an overview of how we characterize the atmospheres of these fascinating objects and some the more recent exciting results to come from ground and space-based telescopes, as well as what the future holds for detailed characterization of short-period exoplanet atmospheres.

Keywords. planetary systems, techniques: spectroscopic

1. Introduction

Some of the first dedicated searches for planets outside of our solar system, or exoplanets, were performed in the 1970's and 1980's using radio telescopes to attempt detection of the radio emission from Jupiter-mass exoplanets (Yantis *et al.* (1977); Winglee *et al.* (1986)). Although unsuccessful, these searches, along with similarly unsuccessful astrometric searches (Lippincott (1977)), jump-started the serious scientific effort to find worlds around other stars.

That effort culminated in 1995 when the first planet around a main-sequence star other than our own was detected. However, the nature of this planet was entirely unexpected: a Jupiter-mass planet on a 4.2 day orbit (Mayor & Queloz (1995)). These planets, subsequently named hot Jupiters due to their very high equilibrium temperatures, are now understood to be fairly common and are present around ≈1% of main-sequence FGK stars (Winn & Fabrycky (2015)). Hot Jupiters are relatively easy to detect due to the large RV amplitudes of their host stars and they have a high transit probability, making them the first planets to have their transit light curves measured (Charbonneau *et al.* (2000)). Finally, it is now understood that hot Jupiter radii are inflated relative to their cooler counterparts and that the high levels of radiation received from their parent stars is responsible (Thorngren & Fortney (2018)).

2. Transmission spectroscopy

Hot Jupiters have large scale heights due to their high atmospheric temperatures and thus are amenable to atmospheric characterization. The primary tool used to measure the structure and composition of these atmospheres is transmission spectroscopy. These measurements consist of comparing in-transit stellar spectra with out-of-transit spectra and looking for small differences that can be attributed to absorption in the planet's atmosphere. The first detection of an exoplanet atmosphere was made using the *Hubble Space Telescope* by Charbonneau *et al.* (2002), who measured Na I absorption around the hot Jupiter HD 209458 b. Ground-based detections would soon follow (Snellen *et al.* (2008); Redfield *et al.* (2008)), demonstrating that hot Jupiter atmospheres can be characterized using fairly standard spectrographs on large telescopes.

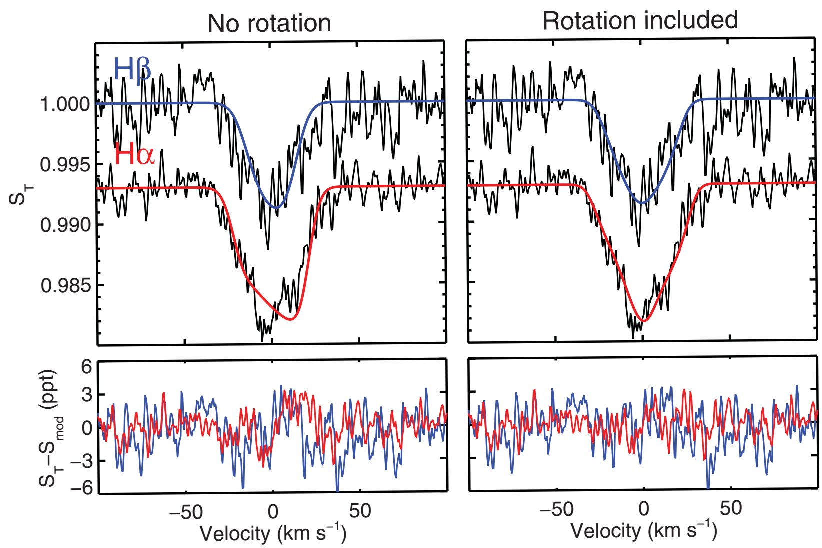

Figure 1. Balmer line transmission spectra and atmospheric models from Cauley *et al.* (2019) for the ultra-hot Jupiter KELT-9 b. The Balmer lines are useful tracers of the upper thermosphere in hot Jupiters.

In general, transmission spectroscopy observations can be split into two categories: low-resolution, which probes broad molecular features and the pressure-broadened wings of atomic lines, and high-resolution, which provides velocity-resolved detail on the cores of atomic lines and individual molecular transitions. The bulk of the important low-resolution observations have been performed by *HST* and have revealed a plethora of atmospheres around hot Jupiters, including everything from featureless spectra to objects with strong H_2O, Na I, K, and Rayleigh scattering signatures (Sing *et al.* (2016)).

High-resolution observations are more amenable to ground-based observing since echelle spectra are most often not flux-calibrated. This allows absorption to be measured against the local continuum rather than in absolute counts or flux. There are two methods of extracting absorption signatures from high-resolution spectra. The first involves a straightforward search for absorption lines in the transmission spectrum, which can often be accomplished manually since the only lines present in a majority of hot Jupiter atmospheres are strong resonance lines, such as Na I D or the Balmer lines (Figure 1). Automated searches that are agnostic to the atomic parameters are also useful if one suspects many different absorbing species. The second method requires a model template of the planet's atmosphere which can be cross-correlated with the transmission spectrum in order to find peaks in the cross-correlation function. This method is especially useful when many weak features are present from the same atom since the signal in the cross-correlation function is increased with each absorption feature. Cross-correlation is also uniquely suited to identifying molecular features in high-resolution near-infrared transmission spectra (Brogi *et al.* (2016)).

3. High-resolution absorption features in hot Jupiter atmospheres

The first feature ever measured in an exoplanet atmosphere was atomic sodium (Charbonneau *et al.* (2002)). Since that pioneering measurement, high-resolution transmission spectrsocopy has revealed a wide variety of atomic and molecular absorption signals in a diverse set of hot Jupiters. Sodium continues to be an important diagnostic

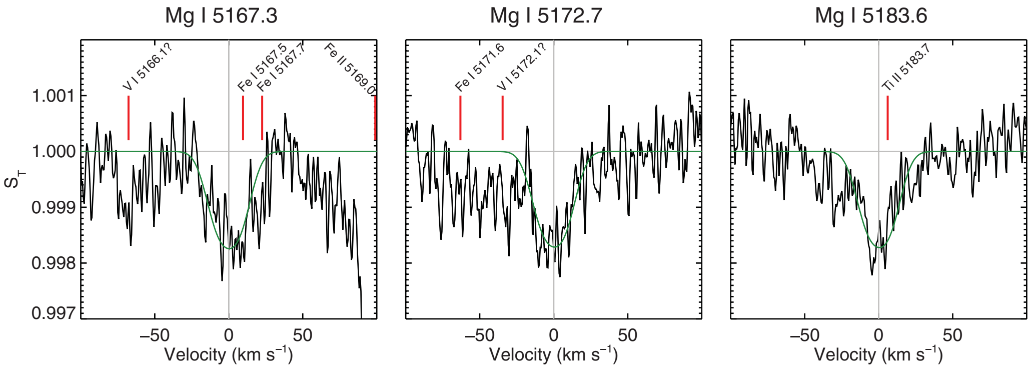

Figure 2. The first detection of the neutral magnesium triplet in an exoplanet atmosphere from Cauley *et al.* (2019) for KELT-9 b. Magnesium is an important coolant in hot Jupiter atmospheres and is a good mass loss tracer.

of the lower thermosphere (Wyttenbach *et al.* (2015); Khalafinejad *et al.* (2017); Seidel *et al.* (2019)). Potassium at 7699 and 7665 Å has also been detected in a number of planets (Sing *et al.* (2016); Keles *et al.* (2019)) and has similar formation conditions as the Na I D lines.

The hydrogen Balmer lines, and most prominently Hα, have become widely used tracers of the extended thermospheres of hot Jupiters (Cauley *et al.* (2015); Jensen *et al.* (2018); Yan & Henning (2018); Casasayas-Barris *et al.* (2019)). Balmer line absorption was first detected around HD 189733 b by Jensen *et al.* (2012) and subsequently confirmed by Cauley *et al.* (2015) and Cauley *et al.* (2016). Balmer line absorption is especially prominent around hot Jupiters orbiting A-type stars, such as KELT-9 b and KELT-20 b, due to the intense UV flux incident on the planet, which produces high rates of ionization and recombination to the $n = 2$ electronic state (Yan & Henning (2018); Cauley *et al.* (2019); Casasayas-Barris *et al.* (2019)).

Recently, absorption in the meta-stable neutral helium line at 10830 Å has been measured around a number of hot Jupiters. This line is a wonderful tracer of the thermosphere due to its ability to absorb photons out to large distances beyond the planet's optical radius (Oklopčić & Hirata (2018)). The first He I 10830 Å detection was made by Spake *et al.* (2018) for the hot gas giant WASP-107 b. This absorption was later characterized from the ground, revealing a cloud of helium extending to twice the planet's optical radius (Allart *et al.* (2019)). A number of He I 10830 Å immediately followed, including for HAT-P-11 b (Allart *et al.* (2018)), HD 189733 b (Salz *et al.* (2018)), WASP-69 b (Nortmann *et al.* (2018)), and HD 209458 b (Alonso-Floriano *et al.* (2019)).

Most spectacularly, the ultra-hot Jupiter KELT-9 b, which has an equilibrium temperature of $\approx$4000K (Gaudi *et al.* (2017)), displays absorption in a number of neutral and singly ionized metals, including Mg I (Figure 2), Fe I and Fe II, Ti II, Cr II, Sc II, and Y II (Hoeijmakers *et al.* (2018); Cauley *et al.* (2019); Hoeijmakers *et al.* (2019)). KELT-9 b also shows prominent Balmer line absorption and is estimated to be losing mass at a rate of $\approx 10^{12}$ g s^{-1} (Yan & Henning (2018); Cauley *et al.* (2019)).

4. Stellar activity and transmission spectra

When looking for atmospheric absorption by strong atomic lines, it is natural to ask whether or not active regions on the stellar surface could be producing the signals rather than the planet's atmosphere. This is possible due to the nature of transmission spectroscopy: during transit the planet occults different portions of the stellar disk at various times during the transit. If the planet occults an active region that is brighter or emits

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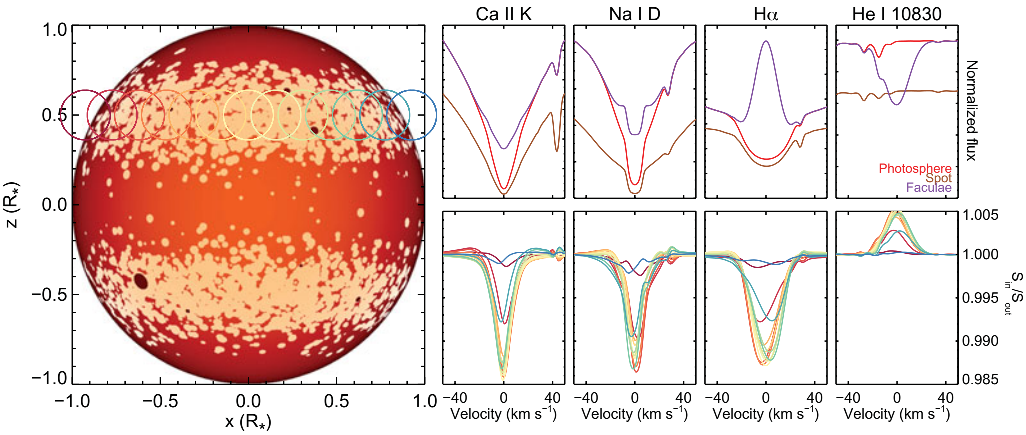

Figure 3. Simulated hot Jupiter transit of a very active stellar surface (left) and the resulting in-transit spectra for Ca II H and K, Na I D, Hα, and He I 10830 Å(bottom right). Transiting active regions can produce signals that mimic absorption in the planet's atmosphere, although the planet must continuously transit strongly emitting active regions to produce a consistent signal.

a different spectrum than the rest of the stellar disk, the difference will manifest in the transmission spectrum as an absorption or emission feature with strength roughly comparable to $(R_p/R*)^2$.

This question was investigated by Cauley *et al.* (2018) specifically for hot Jupiters transiting active stars (see Rackham *et al.* (2018) for a similar exercise involving rocky planets transiting M-dwarfs). They found that in order to produce the strength of the observed transmission spectra for systems like HD 189733 that the planet needs to transit almost directly across an active latitude and that the strength of the chromospheric emission features needs to be similar to the intensity produced by a moderate solar flare. Figure 3 shows an example of a hot Jupiter transiting a very active stellar latitude. Notably, the observed He I 10830 Å absorption signatures cannot be caused by active region transits since He I 10830 Å is in *absorption* in normal stellar chromospheres and thus would produce an emission feature when occulted. Thus stellar activity likely contributes to Balmer, Na I D, Ca II, and He I signals but the specific geometries required make it unlikely that the absorption is due entirely to occulted active regions.

5. Atmospheric dynamics from high-resolution spectra

One of the main advantages high-resolution observations have over low-resolution observations is the ability to resolve velocity features in the transmission spectrum. Hot Jupiters are expected to have extremely powerful winds and jets in their upper atmospheres with velocities on the order of a few kilometers per second Rauscher & Kempton (2014). Even though they are likely tidally liked, the equatorial rotational velocities of hot Jupiters are also on the order of a few kilometers per second. The combination of these strong winds and rotation can shift and broaden line profiles, which can then be extracted using relatively simple models of the atmospheric dynamics.

The first measurement of a hot Jupiter's wind speed was reported by Snellen *et al.* (2010) who showed that the CO signal in the planet's atmosphere was blue-shifted by $\approx$2 km s^{-1}, indicative of day-to-night side winds in the lower thermosphere. Since that pioneering study, only a handful of dynamics signatures have been published in the literature. Among them are jet and wind speeds for HD 189733 b (Louden & Wheatley (2015); Brogi *et al.* (2016); Cauley *et al.* (2017a)), rotation for KELT-9 b (Cauley *et al.* (2019)), and wind speeds and atmospheric expansion for HAT-P-11 b (Allart *et al.* (2018)).

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One of the limiting factors in obtaining a reliable measurement of velocity shifts and line broadening in a transmission spectrum is the signal-to-noise of the transmission spectrum itself. In-transit variability, such as active region transits, can also confuse the velocity centroids. Confident velocity measurements from individual in-transit spectra can only be arrived at using exposures from 10-meter class telescopes (see Cauley *et al.* (2017a) and Cauley *et al.* (2019) for examples). The upcoming era of extremely large telescopes and ultra-stable spectrographs will usher in a new age of atmospheric dynamics measurements for exoplanets by greatly expanding the number of systems accessible to such experiments and increasing the precision of the in-transit observations.

6. Asymmetries due to circumplanetary material

One of the defining features of hot Jupiters is their potentially large mass loss rates. Although not high enough to evaporate a significant fraction of the atmosphere on evolutionary timescales, most hot Jupiters lose enough material to produce observable exospheres. These highly extended atmospheres can produce fantastic transit signals that show striking asymmetric absorption, i.e., absorption strength that changes as a function of time. Unfortunately, the most useful atomic line to measure the exosphere is Lyman-α at 1216 Å and must be observed using a space-based spectrograph. The only instruments currently available to perform these experiments are STIS and COS on the *Hubble Space Telescope*. The limited amount of available *HST* time and the low signal-to-noise at Lyman-α has prevented the detection of a large number of hot Jupiter exospheres.

The most famous of the detected exosphere is that of the hot Neptune GJ 436 b. Ehrenreich *et al.* (2015) reported an enormous transit depth of $\approx 40\%$ in the wings of the Lyman-α line. The transit in Lyman-α began about three hours before the optical transit and continued out to $\approx$30 hours after the optical transit. This incredible feature is nicely explained by a cometary tail of hydrogen atoms that have escaped from the planet and are being swept away from the star by radiation pressure and interactions with the stellar wind. Although not as spectacular, hydrogen exospheres have also been measured around GJ 3470 b (Bourrier *et al.* (2018)), HD 209458 b (Vidal-Madjar *et al.* (2003)), and HD 189733 b (Lecavelier des Etangs *et al.* (2010)).

Asymmetric transit features have also been noted for HD 189733 b using the Balmer lines (Cauley *et al.* (2015, 2016)) and WASP-12 b in the near-UV Mg II doublet (Fossati *et al.* (2010)). Both systems showed an early ingress, suggestive of material orbiting ahead of the planet and crossing the stellar disk before the optical transit. Although the Balmer line signal for HD 189733 b may be due to variability in the stellar activity level, there is evidence that such changes only occur near a planetary transit (Cauley *et al.* (2017b)). Thus the pre-transit signals are likely due to planetary material or some manifestation of a star-planet interaction. WASP-12 b similarly shows variability in the pre-transit absorption (Nichols *et al.* (2015)). Further investigation is needed to understand the nature of these interesting signals.

7. Summary and future prospects

The race has now begun to detect the imprint of biolagically generated gasses in the atmospheres of rocky planets orbiting M-dwarf stars. This is one of the primary exoplanet goals of the *James Webb Space Telescope*. It is important to keep in mind, however, that hot Jupiters still have much to teach us concerning exoplanet atmospheres and, unlike small rocky planets, we have no solar system analog to examine for clues. Such a wonderful class of planets deserves continuing study.

The next generation of extremely large ground-based telescopes will greatly expand the number of transiting hot Jupiter systems for which transmission spectra can be obtained. This will evenutally allow population-level statistics to be obtained on things such as hot

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Jupiter rotation, wind speeds, atmospheric structure, and chemistry. Although we are still in the discovery phase of exoplanet atmospheric characterization, the future is bright and all roads lead to a deeper statistical understanding of these amazing worlds.

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