Compositions of Exoplanets Via High Precision Ground-Based Spectroscopy

1 Introduction

"If a picture is worth 1000 words, then a spectrum is worth 1000 pictures." This adage is especially true in the realm of transiting exoplanets where, in fact, we typically obtain about 1000 spectra of an exoplanet system to separate effects due to the planet from those of the star. The goal is to understand what a planet is made of, what the temperature structure of the atmosphere is and what these pieces of information tell us about the planet. High quality spectra can be used to constrain planetary formation, evolution, mass loss and vertical mixing and also help put the Solar System in context. In extreme cases of evaporating or disintegrating planets that have been eroded from a much larger size, the spectrum of the escaping material gives a rare glimpse into the interior of a planet, something totally inaccessible from Solar System bodies.

While there many hundreds of confirmed exoplanets, only a handful of them have been characterized in the near-infrared. Even among this sample, the near infrared results are not robust because the precision required for characterization (errors $\lesssim 1000$ parts per million) is typical much larger than errors due to telescope motions, telluric (Earth's atmospheric) absorption and detector effects. Followup of these targets and other hot exoplanets is essential for understanding their atmospheres and composition but it requires careful observational techniques and planning to be successful.

2 Experience

I have previously created a collaboration and received observing time for hot Jupiter and disintegrating planet detection. I wrote proposals for the Palomar Observatory, Apache Point Observatory and Infrared Telescope Facility and my team was awarded time on all three facilities to observe hot Jupiters and the disintegrating planet KIC 12557548b. Our team has pushed boundary of planetary characterization by spectroscopically examining the faintest planet-star system at a K magnitude of 12.2 (**Schlawin** *et al.*, 2013).

In addition to observing, I have done instrumentation for the TripleSpec 4 instrument, similar to the Palomar TripleSpec (Herter *et al.*, 2008). My contributions included the refinement of the optical imager design for the J band, construction of cold volume suspension straps and the procurement of the optical components. Additionally, I am updating the slit design to decrease slit losses and perform high precision exoplanet measurements while maintaining high optical throughput. My TripleSpec 4 instrumentation experience gives firsthand knowledge of the instrument, vital to making high precision observations. The experience also gives me the ability to model instrument effects where the models are motivated by slit transmission and the optical chain's response to star variability and motion.

3 Methods

A key method enabling exoplanet atmospheric detection possible is *spectro-photometry.* This is the study of how the star-planet system's flux changes as a function of both time and wavelength. The greatest changes in flux per time happen at primary transit, when the planet passes in front of its host star. Since the primary transit depth depends on the planet to star radius ratio R_p/R_* and the terminator is perpendicular to our line of sight at transit, primary transits are useful for measuring particular atoms and molecules located in the exoplanet atmosphere at the terminator. Additionally, during secondary eclipse, the planet's light becomes occulted by the star and detection of the planet's emission spectrum indicates whether or not there is a stratosphere (temperature inversion) and which molecules absorb or emit along the temperature profile.

Interpretation of the measured light curves requires understanding of the telescope's systematics and the stellar surface, which can sometimes have significant limb brightening. My team's and my modeling of chromospheric emission lines shows how the shape of a light curve at particular ultraviolet wavelengths can differ significantly from typical optical or infrared transits (e.g. **Schlawin** *et al.*, 2010).

I will continue observations of exoplanets using the multi-object spectroscopy (MOS) method (Bean *et al.*, 2010). The MOS method is to divide a target star spectrum by one (or an average of several) reference stars to correct for variability in telluric (Earth's) transmission and response of the instrument. Close proximity of the reference star to the target provides an advantage for calibration as their atmospheric turbulence and telluric fluctuations are highly correlated.

4 Science Goals

The infrared wavelengths from 0.8μm to 2.4μm are a rich place for detecting molecules in exoplanets. H_2O , CH_4, CO_2 and CO all have strong spectral features in the infrared (Tinetti *et al.*, 2010). While some molecular features in exoplanets will be difficult to detect with ground-based methods because of Earth's atmosphere (telluric absorption), other molecules lie in transparent windows that are readily accessible from the ground. Methane can produce spectral features at 1.6 μm and 1.7 μm (Tinetti *et al.*, 2010) and this is conveniently in a wavelength region where Earth's transmittance is relatively clean (Crossfield *et al.*, 2012). Another two molecules that lie in spectral windows are TiO and VO. Though not yet definitively detected in exoplanets, they are important molecules to search for because they may explain the bifurcation of planets into ones with stratospheres and ones without (Hubeny *et al.*, 2003; Fortney *et al.*, 2008). Observations of one planet with a stratosphere indicate that it is not due to TiO and VO (**Schlawin** *et al.*, 2013).

For disintegrating rocky planets such as KIC 12557548b (Rappaport *et al.*, 2012), the infrared spectrum is sensitive to particle size and any gas that may be escaping. Just as Galactic extinction of starlight by interstellar dust reddens distant stars, KIC 12557548b's dust cloud should temporarily redden its host star with the spectral slope set by the dust grains' particle sizes. For escaping gas, however, the infrared spectrum is richer and the molecular bands can reveal what kind of escaping gas may be escaping the planet. Knowing the composition of the gas and the extent of the particle size is crucial for constraining which of the many disintegration mechanisms could be responsible for rocky planet disintegration.

I propose an observational campaign for new transiting exoplanets at faint magnitudes ($K > 11$), many of which were found in the Kepler field and also by ground based transit surveys. The purpose in performing exoplanetary spectro-photometry is to generate an accurate planet to star radius ratio $R_p(\nu)/R_*(\nu)$ as a function of wavelength. $R_p(\nu)/R_*(\nu)$ will refine, confirm and/or reject compositional models for exoplanet atmospheres if it can achieve a precision of 100 ppm. I propose to use a ground-based method to find $R_p(\nu)/R_*(\nu)$ at moderate resolution (R $\sim$ 80 to R $\sim$ 3000).

The ultimate goal of these measurements will be to answer these scientific questions: What role do TiO/VO molecules have in the temperature structure of hot Jupiters? What are the compositions of hot Jupiter atmospheres in comparison to their host stars? What do their compositions imply about the formation of the hot Jupiter's? For disintegrating planets, what is the particle size of the escaping material and what kind of gas is present? Which disintegration mechanisms do these particle sizes and compositions favor? What can we learn about planet formation and evolution from these observations?

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