1 Scientific, Technical, & Management Section

1.1 Overview

Over the past decade, observations of transiting planets and their atmospheres from *Spitzer* and *HST* have transformed the studies of extrasolar planetary atmospheres from simplified model predictions alone to a full-fledged field, with stunning discoveries and unprecedented details. Despite the remarkable progress in both observations and theories, the diverse atmospheres of exoplanets are still poorly understood. Because the atmospheres of planets are tightly related to their interiors and origins, the studies of their atmospheres allow us to understand their diversity and thus to better define the Solar System's place in the Galactic neighborhood. More importantly, detecting and characterizing massive transiting planets paves the way toward our ultimate goal of characterizing nearby Earth-like planets.

To further advance our understanding of exoplanet atmospheres, **we propose a ground-based study of transiting hot Jupiters with a novel, high precision technique – diffuser-assisted photometry. We will apply this new technique to proprietary ground-based telescopes to achieve unparalleled precisions and observing efficiency at wavelengths complementary to *Spitzer*.** By combining our ground-based secondary eclipse measurements with Spitzer data, we aim to provide the necessary broad wavelength coverage and precision to break atmospheric model degeneracies for a large sample of hot Jupiters. We will enable coherent comparative studies that can shed light on the fundamental processes at work in exoplanetary atmospheres, and offer insights into the origins of those planets. Since Spitzer will be unavailable soon and JWST will not come on line for quite a few years, our ground-based observations will be critical for the understanding of exoplanet atmospheres. **We are essentially extending the legacy of *Spitzer* to the ground by carrying out a substantial sample of exoplanet atmosphere measurements with high precision.** This work will also provide high-precision ground-based techniques for future TESS follow-ups, and will strongly inform targeting and science goals for studies of giant planet atmospheres with JWST.

This proposal supports the objectives of Origins of Solar Systems because it aims to characterize exoplanetary systems with an emphasis on obtaining new observables. Our proposal falls into the categories of: *Characterization of extra-solar planets to explain observations of extra-solar planets, and improving understanding of the origins of planetary systems.* Our research has direct relevance to NASA's Strategic Plan, specifically Strategic Goal 2 (*Expand scientific understanding of the Earth and universe in which we live*), Outcome 2.4 (*Discover how the universe works, explore how it began and evolved, and search for Earth-like planets*), and Objective 2.4.3 (*Generate a census of extra-solar planets and measure their properties*).

1.2 Introduction

Transiting exoplanets provide an unparalleled opportunity to directly study planetary atmospheres without the need to spatially resolve them from their host stars (Figure 1). As a planet passes in front of its host star (primary transit), the small decrease of starlight provides a measure of the planet-to-star radius ratio and the scale height of the plane-

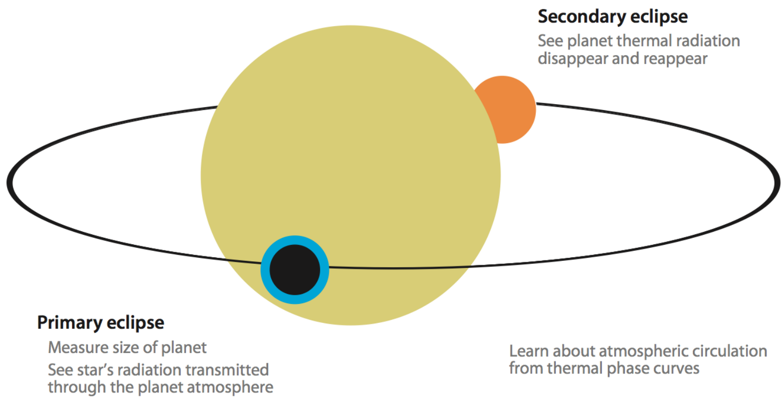

Figure 1: Schematic of a transiting exoplanet and corresponding follow-up measurements (Seager & Deming, 2010). Primary eclipse is also called a transit.

tary atmosphere. Since the scale height of the atmosphere directly relates to its chemical composition, measuring the radius ratio at different wavelengths (i.e., the transmission spectrum) provides direct constraints to the atmospheric composition at the planet's terminator region (Charbonneau et al., 2002; Swain et al., 2008). On the other hand, as a planet passes behind its host star (secondary eclipse), the occultation of the planet causes a much smaller decrease of the total light, providing a direct measure of the dayside emission from the planet itself. When measured at multiple wavelengths, the emission spectrum of a planet enables the study of planetary atmospheric temperature-pressure structure, chemical compositions, and heat recirculation (e.g., Figure 2). The atmospheric compositions of these planets can also shed light on where and how they formed, because oxygen- and carbon-rich ices condense at different distances from their stars, and the resulting systematic variation of the C/O ratio in the protoplanetary disks may imprint signatures in the planetary atmospheres (Öberg et al., 2011).

Due to the high brightness contrast between planets and their host stars, studies of exoplanetary atmospheres have been mostly limited to close-in planets, particularly a class of close-in gas giant planets known as hot Jupiters. These planets typically orbit at distances of less than 0.05 AU from their host stars, and have temperatures comparable to those of the coolest stars ($\sim$1000 - 3000K) with correspondingly exotic atmospheric chemistry due to strong stellar irradiation. Unlike Jupiter's atmosphere, where many common molecules have condensed out into difficult-to-measure cloud layers, hot ($>\sim$1500 K) planets make ideal targets for studies of atmospheric composition, as virtually all atmospheric constituents should exist in gas phase. Their relatively high temperatures and large radii make them ideal candidates for near and mid-IR eclipse measurements, as they exhibit favorable secondary eclipse depths in these wavelengths.

The first detections of thermal emission from exoplanets were achieved by *Spitzer* in 2005 for two hot Jupiters, TrES-1b and HD 209458b (Charbonneau et al. 2005; Deming et al. 2005). In the years since these initial studies, astronomers have succeeded in directly detecting the infrared light from several hot Jupiters, thanks to the improvements in observing techniques and more importantly, the discoveries of a large number of hotter planets by dedicated surveys. Currently, about three dozen hot Jupiters have had their thermal emission directly detected by photometric and/or spectroscopic measurements from space and/or ground, most of which were achieved by the *Spitzer Space Telescope*. Most recently, thermal emission from the super Earth 55 Cnc *e* has also been detected with the warm *Spitzer* at 4.5 μm (Demory et al., 2012), thanks to the development in observation and data analysis techniques from studies of hot Jupiters.

1.2.1 Current understanding of hot Jupiter atmospheres

Based on the impressive *Spitzer*, *HST* and new ground-based results, studies of transiting planets have yielded an abundance of information on their atmospheric characteristics. In the UV and optical, alkali lines from sodium and potassium, and HI lines such as Ly-α and H-α have been detected in the transmission spectra of the atmospheres or exospheres of several hot Jupiters (Charbonneau et al., 2002; Redfield et al., 2008; Colón et al., 2010; Sing et al., 2011; Lecavelier Des Etangs et al., 2010; Jensen et al., 2012, etc.). In the infrared, molecules including H_2O, CH_4, CO_2, and CO, have all been found from both transmission spectra and thermal emission spectra (e.g., Barman et al., 2005; Barman, 2008; Knutson et al., 2008; Swain et al., 2008, 2009b; Burrows et al., 2008, etc.).

Observations of hot Jupiters' atmospheres have revealed that hot Jupiters are in fact not a homogeneous group, despite superficial similarities in their masses and radii. Some planets are found to have a temperature inversion layer in their upper atmospheres (like the inverted temperature profile of the Earth's stratosphere) that leads to water emission instead of absorption in their spectra, whereas others do not have such inversion (e.g., Knutson et al., 2008; Burrows et al., 2008; Fortney et al., 2008; Charbonneau et al., 2008; Deming et al., 2006; Swain et al., 2009b). It is believed that additional opacity sources in the upper atmosphere are responsible for the inversions, but the nature of the sources is unknown, although TiO, VO, and sulfur compounds produced by photochemistry were proposed (e.g., Burrows et al., 2008; Zahnle et al., 2009). Earlier studies suggest that hot Jupiters can be categorized based on their irradiation levels into a hotter group with temperature inversion and a cooler group without inversion (Fortney et al., 2008). However, as more observations and larger samples emerge, it appears that there is not a tight correlation between atmospheric temperature and the presence or absence of an inversion (Madhusudhan & Seager, 2010). Recently, a survey by Knutson et al. (2010) found a correlation between stellar activity and the presence/absence of thermal inversions. They suggested that increased UV flux from active stars destroy the compounds responsible for the formation of the observed temperature inversions, making inversion layers absent in planets orbiting chromospherically active stars.

Hot Jupiters experience extremely strong irradiation from their host stars due to their close-in and typically tidally-locked orbits. The resulting heat and large temperature gradient between the permanent dayside and the nightside can induce circulations and strong zonal winds to redistribute the energy in some cases, which may also affect the vertical temperature structure and mixing in the atmosphere. Atmospheric heat recirculation efficiency of hot Jupiters, together with their albedos, offer insights into their total energy budget and dynamical processes. The recirculation efficiency and albedo can be determined if both the dayside and nightside temperatures or phase modulation of the light curve can be measured, as in the case of HD 189733b (e.g., Knutson et al. 2007). Hot Jupiters with

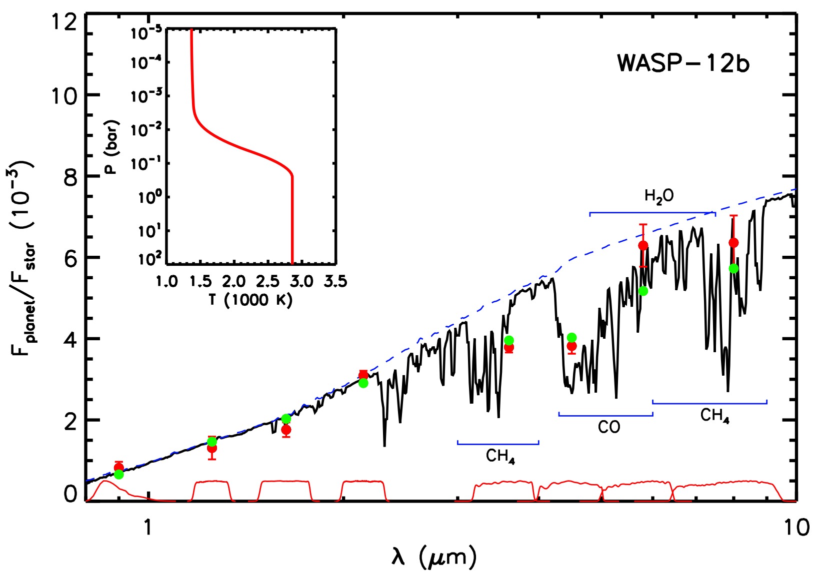

Figure 2: Multi-band observations of WASP-12 and atmospheric model (Madhusudhan et al., 2011). The ground-based observations (from 0.9 to 2.2 μm), together with the *Spitzer* measurements (3.6, 4.5, 5.8, 8 μm), completes the SED of the planet, providing stringent constraints to its atmospheric properties and revealing its high C/O ratio and weak thermal inversion. Although there is some debate over the interpretation of these broadband data (e.g., Madhusudhan et al., 2011; Crossfield et al., 2012), the current consensus is that this planet possibly has a super-solar C/O ratio. This multi-band study demonstrates the leverage and necessity provided by the combination of ground-based measurements and *Spitzer* results.

temperatures >2400K are usually found to have very low global recirculation efficiency and huge day-night temperature contrast, while cooler planets have a wider variety of recirculation efficiency and lower day-night contrast (Cowan & Agol, 2011). Thermal inversion was first proposed to explain the low heat transport efficiency in hot planets because additional opacity sources in the atmosphere can reduce recirculation. However, Cowan & Agol (2011) recently found that the correlation is very weak, and the sharp transition at 2400K remains unexplained.

1.2.2 Importance of new near-IR multi-wavelength data

Despite the recent progress in both observations and theories, the diverse atmospheres of hot Jupiters are still poorly understood. Key questions like the nature of temperature inversions, the cause of low heat recirculation in the hottest planets, and the peculiar chemistry and composition in some atmospheres, etc., are still not fully answered. Currently, most detections of planetary atmospheres were made by the *Spitzer Space Telescope* thanks to its outstanding photometric capability in the near and mid-IR. However, due to limited wavelength coverage and degeneracies in atmospheric models, using only a few *Spitzer* broadband measurements (currently limited to only 2 IRAC bands) is not enough to make robust claims on the presence of thermal inversions and the chemical abundances in many cases (e.g., Figure 3). Some signs of thermal inversion can in fact also be explained without thermal inversion by unusual but still plausible compositions (Madhusudhan & Seager, 2010; Deming et al., 2012; Blecic et al., 2013).

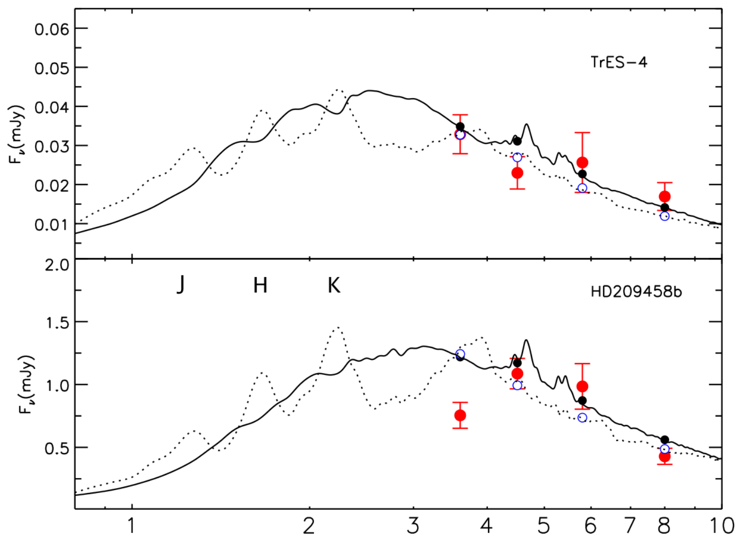

Figure 3: Comparison of two model cases, with (solid) / without (dotted) a temperature inversion, to Spitzer-IRAC observations (based on Barman et al., 2005; Barman, 2008). The additional information provided by high precision near-IR J, H, K_S observations can break the degeneracy and help distinguish between the two cases.

On the other hand, because ground-based near-IR observations allow us to probe the wavelength regions where most of the bolometric output of the planet appears but are not available to *Spitzer*, they can provide additional constraints to planetary spectra, and thus help break degeneracies amongst differing atmospheric pressure-temperature profiles and chemistries (Madhusudhan & Seager 2009), and provide better constraints to thermal inversions in hot Jupiters (see Figure 3). One typical example is the recent studies of WASP-12b, which demonstrate the leverage provided by the combination of high-precision ground-based near-IR and *Spitzer* mid-IR secondary eclipses (Figure 2).

Over recent years, ground-based photometric observations have emerged as an important tool to study planetary atmospheres. More than a dozen hot Jupiters have had their secondary eclipses detected with ground-based facilities (e.g, Sing & López-Morales, 2009; Gillon et al., 2009; López-Morales et al., 2010; Rogers et al., 2009; Alonso et al., 2010; Croll et al., 2010a,b; Zhao et al., 2012a,b; Deming et al., 2012; Bean et al., 2013, etc.). However, because this striking breakthrough is so new, most of the ground-based detections are still limited to single-band measurements. The number of hot Jupiters with multi-band ground-based secondary eclipse observations are limited to only 6: HD 189733b, WASP-12b, CoRoT-1b, WASP-33, WASP-19b, and WASP-43b (Rogers et al., 2009; Alonso et al., 2010; Croll et al., 2010a,b; Swain et al., 2010; Zhao et al., 2012a; Deming et al., 2012; Bean et al., 2013; Wang et al., 2013). Furthermore, most ground-based measurements do not have sufficient precision to constrain models, strongly limiting our understanding of the atmospheric properties. **To break the degeneracies and put stringent constraints on atmospheric models, both high-precision observations and wide wavelength coverage are absolutely essential.** A coherent sample with broad wavelength coverage and high precision is much more meaningful than those obtained in disparate ways.

Because the atmospheric compositions of these planets can shed light on where and how they formed, observations of their atmospheres will help us further understand their diversity and better define the Solar System's place in our Galactic neighborhood. More importantly, characterizing these giant and hot planets serves as a stepping stone for detection and characterization of super-Earth planets, like the case for 55 Cnc e's thermal emission (Demory et al. 2012), and eventually the nearby Earth-like planets.

1.3 Objectives

Based on our team's broad expertise in observational and theoretical characterization of exoplanetary atmospheres from both ground and space, we propose a systematic ground-based observational study of hot Jupiter atmospheres using a novel technique: diffuser-assisted near-IR photometry. We will focus on secondary eclipse measurements in the near-IR J, H, and K_S bands to provide high-precision constraints to the thermal emission spectra of a significant sample of hot Jupiters, and combine with available space observations for detailed and tailored atmospheric modeling. Our objectives are:

1. To provide multi-band measurements to an extended sample of hot Jupiter atmospheres to help better understand the key aspects of their atmospheric properties: chemistry and composition, heat recirculation, and thermal inversion.

Atmospheric Chemistry and Composition: Our ability to constrain the composition and chemistry of hot Jupiter atmospheres are limited by the wavelength coverage available. Our new near-IR measurements, when combined with *Spitzer* measurements at longer wavelengths (and also *HST* data in some cases), will provide broader wavelength coverage to an extended number of atmospheres, opening windows to a better understanding of their chemistry and compositions. A better constrained chemistry and composition model can help us explore many other important questions of these planets such as their formation history, as the systematic variation of the C/O ratio in the protoplanetary disks may imprint signatures in the planetary atmospheres (Öberg et al., 2011).

It has recently been suggested that the chemical composition of several hot Jupiters may be well out of chemical equilibrium with extreme CO or CH_4 mixing ratios. The prime suspects for this departure from equilibrium are vertical and horizontal mixing. The modeling of this phenomena has primarily been *ad hoc* in most studies (but see Moses et al., 2011, for a more thorough study) and many questions remain. Fortunately, CO and CH_4 have strong absorption bands across the near-IR, meaning that our proposed study will provide new insight into the magnitude and diversity of mixing-induced non-equilibrium chemistry of exoplanets. This knowledge will feed back into the atmosphere modeling that we will use to interpret all of our observations.

Temperature Inversions: The presence or absence of temperature inversion in exoplanets is tied to the composition of their atmospheres. The opacity source responsible for atmospheric temperature inversions in hot Jupiters is still unknown. While it is straightforward to achieve extreme temperature inversions at very low pressures, it is not so easy to produce them down to the IR/near-IR photosphere. The obvious candidate is TiO, but it is also unclear if TiO can be well maintained in the upper atmosphere given its high molecular weight and the possible existence of day-night cold traps (Hubeny et al., 2003; Fortney et al., 2008; Spiegel et al., 2009). Instead, sulfur compounds produced by photochemistry were suggested to be possible absorbers to explain these inversions (Zahnle et al. 2009). Uncovering this mystery absorber has proved to be challenging and *Spitzer* observations alone are often not enough to distinguish between atmospheres with or without TiO-induced temperature inversions (e.g., Madhusudhan & Seager, 2010; Deming et al., 2012; Blecic et al., 2013, etc.). By expanding our observations and model study to near-IR wavelengths, we will have increased leverage over temperature as a function of depth and, thus, on the potential opacity sources that could be causing the inversion.

Global Circulation and Albedo: The strong incident stellar flux experienced by hot Jupiters is expected to be advected to the nightside of the planets and re-radiated at different wavelengths, while a small fraction of the flux is reflected back into space. The physical parameters that describe these processes are the planets recirculation efficiency and Bond albedo. By measuring the bolometric flux of either the day or night side (and assuming that the planet's intrinsic contribution is small), one can estimate the Bond albedo and the fraction of energy that is being redistributed by global circulations, although full phase coverage of the flux ratios are much more constraining. By extending secondary eclipse (i.e. dayside) flux measurements to the near-IR (i.e. near the peak flux of the planet), improved bolometric measurements can be made (Cowan & Agol, 2011). Seeking such measurements for a wide variety of planets will lead to a better understanding of how the efficiency of global circulation varies across planets of different stellar hosts, orbital period, planet mass, and so forth. Such a study would provide new and valuable data to compare to modeling of 3D circulation. Moreover, since global circulation and zonal winds driven by intensive stellar irradiation are linked to the persisting mystery of "inflated" hot Jupiter radii through unknown deposition mechanism, this study would also provide more data for further theoretical investigations (e.g., Perna et al., 2012; Rauscher & Menou, 2013; Spiegel & Burrows , 2013, etc.).

2. To enable a coherent comparative study of hot Juptiers, and shed light on the global understanding of their atmospheres.

Comparative and statistical studies have been key to gain a global picture of planetary atmospheres and to reveal the hidden trends that have underlying physical implication and connection to the atmosphere, interior, and formation of the planets. For instance, using a sample of ∼17 planets with detected emission spectra, Knutson et al. (2010) found that planets without thermal inversions in the atmospheres are found orbiting the most chromospherically active stars, while those with thermal inversions are found orbiting quiet stars. The reason could be that the increased UV flux received by planets orbiting active stars destroy the compounds responsible for the formation of the observed temperature inversions.

In the early days of exoplanet atmosphere modeling it was also predicted that hot Jupiters would show extreme day-to-night circulation patterns capable of carrying a large fraction of the incident stellar flux to the night side. Atmospheres with temperature inversions are expected to have inefficient circulation due to the deposition of starlight at higher altitudes. However, in a recent statistical analysis of the albedos and global recirculation efficiencies of 24 transiting planets with secondary eclipse detections, Cowan & Agol (2011) found that differences in recirculation efficiency do not appear to be correlated with the presence or absence of a temperature inversion. Meanwhile, the very hottest Jupiters have lower heat redistribution efficiency and are qualitatively different from the merely hot

Jupiters. These statistical studies rely mostly on the data from *Spitzer* because of the large size and coherence of the *Spitzer* sample. Data from ground-based observations are highly complementary and valuable, but are currently very limited and fragmented. The new ground-based survey-like observations proposed in this study will expand the sample and provide additional and valuable information to better constrain the atmospheric properties, permitting further verification and investigation of the statistical trends and hypotheses.

1.4 Proposed Work

We use differential photometry to reach the precision required to detect secondary eclipses of exoplanets: namely we need a wide field-of-view to ensure many comparison stars for flux calibration, a stable pointing to mitigate flat-fielding errors, and we defocus the telescope to mitigate flat-fielding errors and increase observing efficiency. To make definite progress on the objectives mentioned above, our proposed work has the following two components.

1.4.1 New measurements of planetary atmospheres with a novel technique: diffuser-assisted photometry

Developing novel techniques and observing schemes is an important way to lift the capability of available instruments for better and cutting edge science. Our group has already developed a new observing mode for the Wide-field InfraRed Camera (WIRC) at the Palomar 200-inch telescope, and have undertaken extensive observations of secondary eclipses. In particular, we have developed a new guiding capability for WIRC in coordination with Palomar staff, and have significantly improved the guiding precision by a factor of $\sim$7 (Figure 4). Because the strong inter-pixel variation of infrared detectors is a major source of systematics in high precision photometry, highly stable and precise guiding is key to the detection of secondary eclipses. Our effort has significantly improved the photometric precision of WIRC. Since 2011, we have successfully detected secondary eclipses of 8 hot Jupiters: CoRoT-1b (Zhao et al., 2012a), WASP-3b (Zhao et al., 2012b), WASP-48b (O'Rourke et al. 2013, in prep.), HAT-P-32b (Zhao et al. in prep.), WASP-43b, TrES-5b, Qatar-1b, and WASP-51b (see Figures 4, 5, and 6). Our current detections will almost double the sample of published near-IR ground-based secondary eclipses for exoplanets. Currently, we can regularly reach a precision of $\sim$0.02-0.03% (200-300 ppm) in both H and K_S under good observing conditions – this is comparable to the precision of the corresponding *Spitzer* measurements (e.g. Figure 5 right panel), and is comparable to the best secondary eclipse precision reached from ground (e.g. $\sim$150ppm, Croll et al., 2010b). This precision is already sufficient to allow us to extend the observations to a number of hottest Jupiters in the near-IR. Nonetheless, we are currently still a factor of $\sim$6 above the photon noise limit due to a systematic noise floor, leaving plenty of room for further improvements.

The uniqueness of our proposed observations is to use a novel, diffuser-assisted technique to achieve higher photometric precision. In addition to centroid stability, another key to improving the photometric precision is to spread the starlight to a large number of pixels on the detector and keep the point spread function (PSF) as even and stable as possible. This can improve not only the duty cycle of the observations,

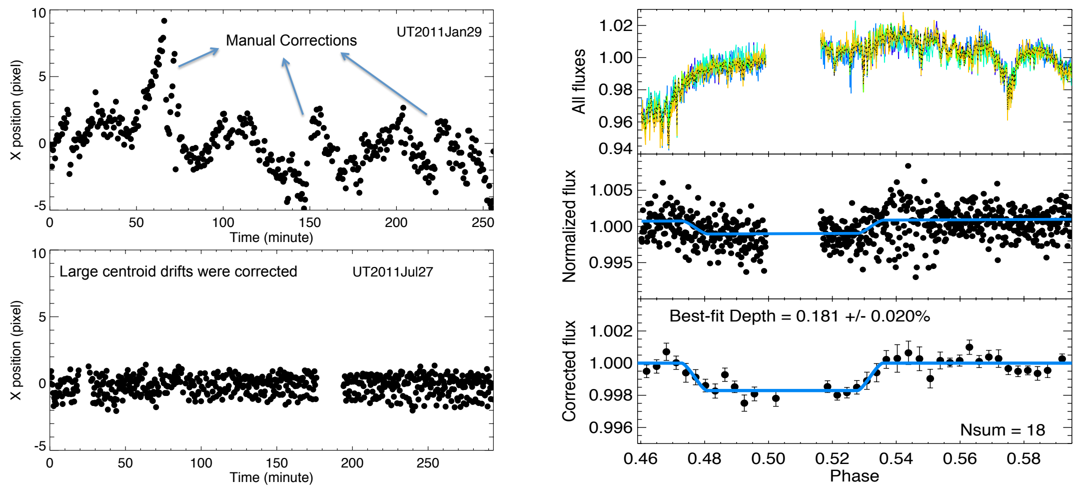

Figure 4: **Left:** Comparison of the centroid drifts before and after implementing our new guiding algorithm. The centroid positions drifted at a speed of ∼10 pixels per 20min in the top panel, causing huge systematics to the light curve. After applying the new guiding scheme, the centroid drift was mostly corrected, resulting in a fluctuation of only ∼2 pixels caused by periodic telescope gear oscillation. **Right:** The resultant Palomar/WIRC detection of the secondary eclipse of WASP-3b in K_S after applying the new guiding scheme. The top panel shows the normalized flux of all calibrators and the target – we typically use more than 5 flux reference stars to calibrate the common-mode variations in the light curve. The middle panel shows the calibrated light curve of the planet. The bottom shows the averaged light curve, with a 9-σ detection of the secondary eclipse (Zhao et al., 2012b).

but also mitigate the large inter-pixel variations of the IR detector. Current photometric observations mostly take the approach of defocusing the telescopes to spread out the light. It is, however, hard to maintain the evenness of a defocused PSF, since the defocused PSF of a telescope usually suffers significantly from telescope astigmatism, which changes with temperature and pointing position, and the atmospheric seeing is usually variable and unpredictable (Figure 7). Our approach to address this issue is to use an engineered holographic diffuser to evenly spread the PSF while keeping the telescope well focused, providing an even and controlled PSF with little dependence on the astigmatism and seeing. Figure 7 demonstrates the effectiveness of a test diffuser in spreading and smoothing the PSF. This technique has the potential to transform our picture of hot Jupiter atmospheres with high-precision photometry for a large sample of exoplanets through both transits and secondary eclipses, including cooler planets and those orbiting fainter stars that are not accessible by emerging high precision multi-object spectroscopy.

We have already ordered a custom designed diffuser for Palomar/WIRC (led by Co-I Knutson) to create a smooth "top-hat" PSF with a FWHM of 3 arcsec. The diffuser is planned for installation in August 2013 and will be used for pilot observations in Fall 2013. Despite our successful detections of secondary eclipses of 8 hot Jupiters without the diffuser, our observations were still a factor of ∼6 above the photon noise limit, due to the aforementioned PSF variations and the existence of varying bright spots in the PSF caused by astigmatism. With the diffuser, we estimate that we will have a gain of 50-100% in observing efficiency (primarily due to the removal of the bright spot in the defocused

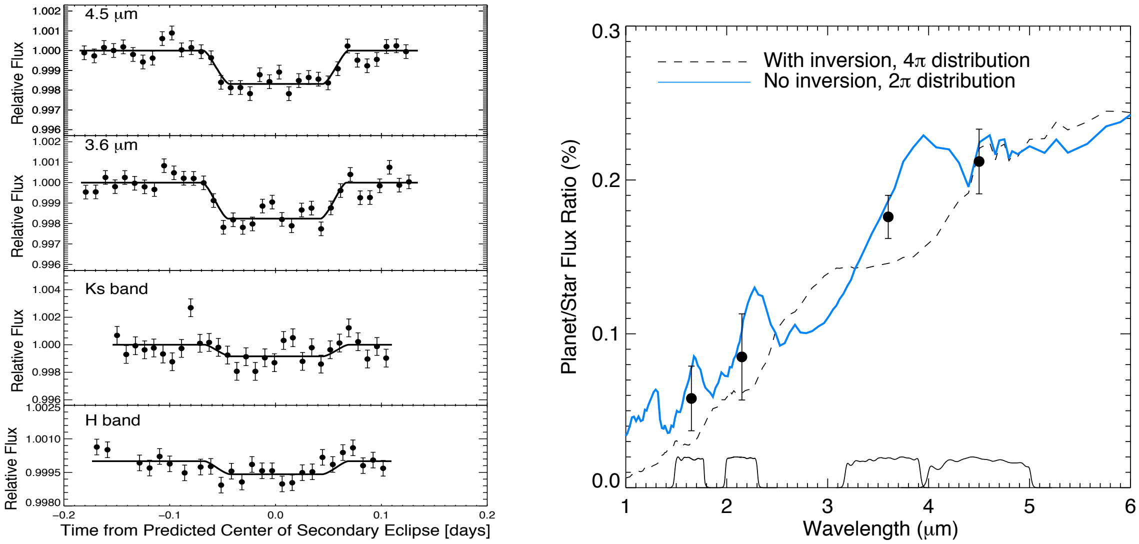

Figure 5: **Left:** Our WIRC + *Spitzer* secondary eclipse observations of WASP-48b (O'Rourke et al. 2013, in prep.). **Right:** Corresponding atmosphere models for our WIRC + *Spitzer* results (based on Fortney et al., 2008). The solid line shows an atmosphere model with very inefficient day-to-night recirculation and no thermal inversion, which is preferred by our data. The dashed model has a thermal inversion and very efficient recirculation. Both models have solar abundance. Note that even without the diffuser, our H & K_S precisions are already comparable to that of the *Spitzer* at 4.5 μm. We expect our new H and K_S band observations of WASP-48b with the diffuser to have errors that are a factor of three smaller due to increased observing efficiency and reduced instrumental systematics, providing more stringent constraints to the models.

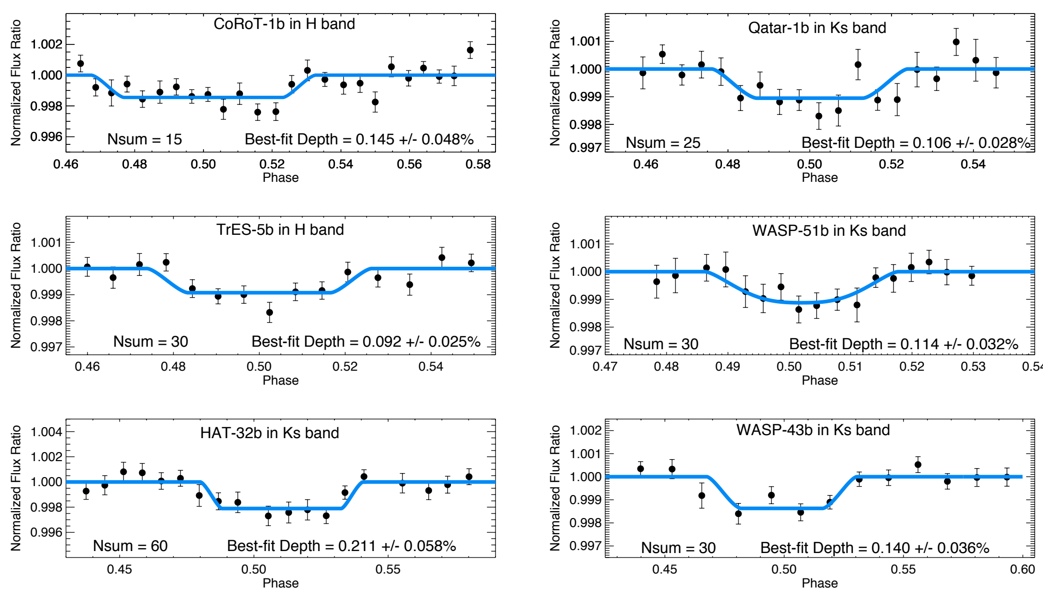

Figure 6: Summary of our Palomar/WIRC secondary eclipse detections of another 6 hot Jupiters in addition to Figures 4 & 5. Our detections now account for ∼40% of all hot Jupiters that have been detected at secondary eclipses from the ground. Currently, we can regularly reach a precision of ∼0.02-0.03% (200-300 ppm) in H and K_S under good observing conditions. With the diffuser, we expect to have at least a factor of 3 improvement in precision due to increased observing efficiency and reduced instrumental systematics.

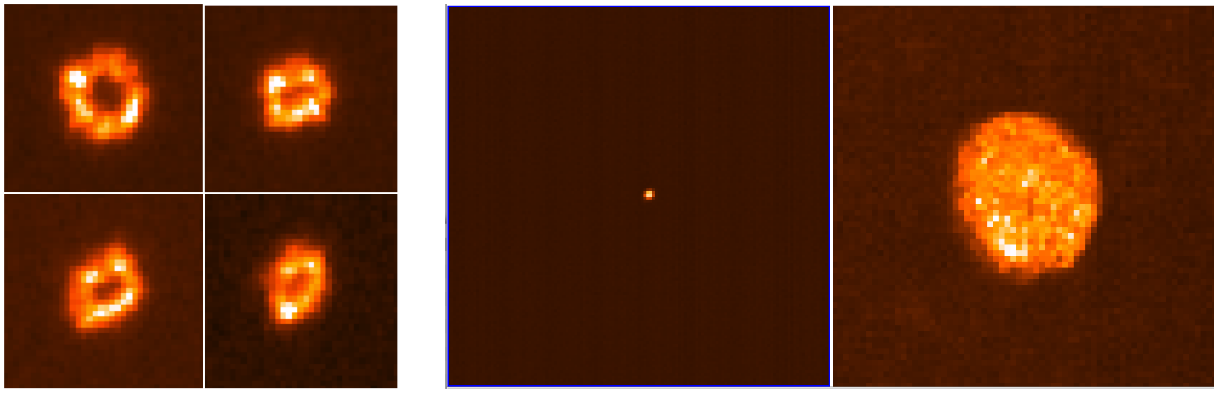

Figure 7: **Left:** Variations of a target's PSF over a typical night, observed with Palomar/WIRC. The defocused PSF varied dramatically over a duration of 5 hours (from airmass of 1.1 to ∼1.6) due to seeing, temperature changes and telescope astigmatism. The astigmatism caused varying bright spots in the defocused PSF, inducing large time-correlated systematics to the secondary eclipse light curve that limits our precision. **Middle and Right:** Our lab test of the effectiveness of a holographic diffuser in spreading out light evenly. The middle panel shows a small PSF from an infrared laser. The right panel shows the PSF after going through the diffuser, which spreads the PSF into a circular "top-hat" shape. The speckles in the diffused PSF were due to the intrinsic speckles and coherence of the laser. With broadband light and atmospheric scintillation, the diffused PSF will be even and smooth. We have already ordered a custom designed and engineered diffuser to fit the specifications of WIRC, and will install it in the filter wheel in August 2013. The ability to mold the PSF evenly and smoothly provides a unique advantage to reach high precision photometry from the ground. This approach has the potential to transform our picture of hot Jupiter atmospheres with high-precision photometry for a large sample of exoplanets (see Figure 8).

PSF, which limited our integration times and the duty cycle), and should eliminate the dominant systematic noise component caused by variations in the PSF over the night. **We therefore expect to gain at least a factor of three in precision relative to our current best detections, reaching precisions well below 0.01% (100 ppm). More importantly, we expect that we can consistently reach these precisions without the need to rely on ideal observing conditions** – this makes us much more efficient with our use of telescope time, as current ground-based observations essentially all rely on the ideal observing conditions to reach their best precision.

We will carry out diffuser-assisted photometry of secondary eclipses with Palomar/WIRC in the J, H, and K_S bands. Our improved precision will provide us the capability of detecting secondary eclipses for an extended sample of at least 35 hot Jupiters with high significance (Figure 8). Nonetheless, our observing philosophy is to first focus on a relatively small sample of ∼12 best targets (4 targets/year) to obtain good wavelength coverage with high precision, and combine with available *Spitzer* data (available through Co-I Knutson; and HST data in some cases) for atmosphere modeling. A broadly measured SED can lift model degeneracies and lead to a better understanding than the alternate approach to obtain single-band flux ratios for a larger number of objects.

In addition to Palomar/WIRC observations, we will also migrate our successful experience to Magellan/FourStar to cover Southern Hemisphere objects. Fourstar is a newly

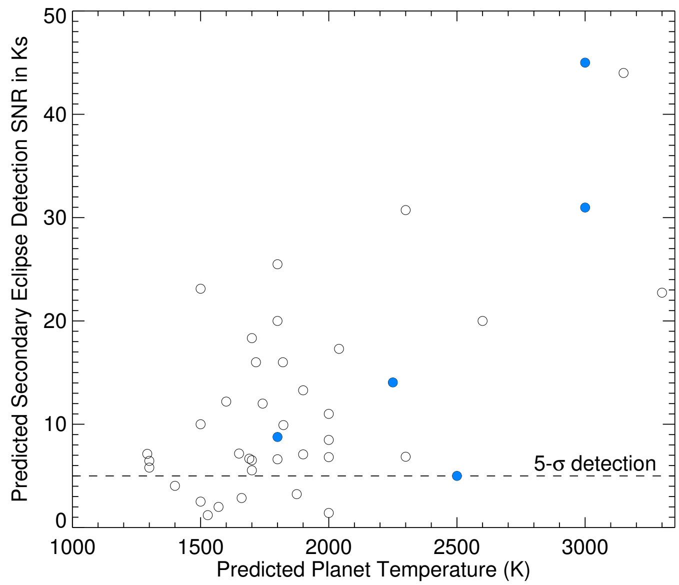

Figure 8: Predicted detection signal-to-noise for a selection of hot Jupiters for our new diffuser-assisted technique. About 35 hot Jupiters can be detected with at least 5-σ significance in K_S-band with the diffuser. The solid blue dots represent the hot Jupiters that currently have published multi-band ground-based data. The rest of the sample either have no ground-based detections or only single-band observations. Using our unique approach, we will significantly expand the current sample with high precision multi-band measurements.

commissioned wide-field near-IR camera at the Magellan Baade telescope covering J, H, and K_S bands. Its large field of view (10.8' × 10.8') and new IR detector (HAWAII-2RG) provide the capability of delivering high precision differential photometry. We will implement a similar engineered diffuser to work with FourStar for high precision photometry of secondary eclipses. We will first focus on ∼2-3 good targets as a pilot program to develop corresponding observing experiences for a more extended program in the future.

Our team has extensive expertise in the data reduction and analysis required in this project. It will be straightforward to adapt our current pipeline for diffuser photometry. We had experience with near-IR photometry using the Magellan Baade telescope in the past. It will also be straightforward to convert our existing pipeline for the new FourStar observations at Baade .

Our team has proprietary access to the proposed observing resources to carry out this research. Specifically, Professor Knutson has institutional access to Caltech's Palomar Observatory, while Professor Monnier has institutional access to Magellan telescopes for the southern targets.

1.4.2 Tailored, detailed atmospheric modeling

The scientific potential of our new atmospheric observations would remain unfulfilled without a serious attempt to incorporate them into state-of-the-art models of our target systems. Co-I Barman is co-developer of the PHOENIX model atmosphere code and leads the effort to maintain and improve its ability to model extrasolar planetary atmospheres. In its default usage, PHOENIX solves the full, self-consistent, 1-D model atmosphere problem under the assumptions of hydro-static, radiative-convective and local chemical equilibrium (CE) as well as local thermodynamic equilibrium (LTE). PHOENIX includes the option of either plane-parallel or spherically symmetric geometry. The atmosphere models are iterated such that the opacity, chemistry, temperature structure, spectrum and so forth are all self-consistent. The mixing ratios of important chemical species are not arbitrarily specified (though it is certainly easy to do so), but are determined by the final solution.

Recently, non-equilibrium chemistry following Smith (1998) has been included as an option for PHOENIX (Barman et al., 2011). This allows for the exploration of mixing-induced departures from chemical equilibrium of important molecules such as CO, CH_4, N_2, and NH_3. PHOENIX also includes several phenomenological cloud models that can be invoked to study the effects of hazes or thicker clouds. All of these are solved within the model atmosphere iterations until global convergence is reached (and energy is conserved).

With over a decade of development, PHOENIX is fast, flexible and robust. With it, we will be able to explore a wide variety of plausible atmospheric scenarios to interpret our observations. With photometric and spectroscopic data in hand, we will be able to fit model results and infer basic properties (e.g. bolometric luminosity). Our broad wavelength coverage will allow us to probe the atmospheres over a broad range of optical depths and, thus, infer the temperature structure. In situations where the fully consistent 1-D atmosphere does not match the data, we always have the option of prescribing a variety of temperature and chemical properties (e.g. as done by Madhusudhan & Seager, 2010) to obtain an estimate of the properties allowed by the observations. Even in the instances of non-detections, ground-based data can often be used to eliminate certain models (Crossfield et al., 2011) and provide useful limits on atmospheric properties.

Finally, with Barman's expertise and direct access to the models, our group will have the ability to explore new ideas (e.g., new opacity sources) inspired by the new observations.

1.5 Scientific significance and relevance to NASA missions

The depth and coherence of our proposed work is unique and unparalleled from the ground. Our new approach of using diffuser-assisted photometry will provide higher precision measurements than current ground-based observations and will push the ground work to a new level. With institutional access to Palomar (from Professor Knutson) and Magellan telescopes (from Professor Monnier), we will cover both the Northern and Southern Hemispheres. We aim to provide a consistent set of new-IR J, H, K_S band measurements to a focused sample with high precision. This is different from the currently available ground-based measurements as most of them are single-band and scattered in H, K_S, z', or narrow bands. As pointed out in a few statistical studies, a coherent and uniform data set is more meaningful than those obtained in disparate ways (e.g., Cowan & Agol, 2011).

Our near-IR observations are highly complimentary to the *Spitzer* broadband measurements. Co-I Knutson provides access to the large set of new *Spitzer* data, providing a truly broad wavelength coverage that is critical for a comprehensive planetary atmosphere characterization (J, H, K_S, 3.6 μm, 4.5 μm, and in some cases 5.8 μm & 8 μm archival data). **We are essentially extending the legacy of *Spitzer* to the ground by carrying out a substantial sample of exoplanet atmosphere measurements with high**

precision. Since *Spitzer* will be unavailable soon and JWST will not come on line for quite a few years, our ground-based observations are critical for the understanding of exoplanet atmospheres.

In addition, PI Wirght and Co-I Knutson are also experienced awardees of *HST* observations. We will also propose and carry out additional follow ups of a prioritized list with *HST* and/or Keck/MOSFIRE (through Knutson's access to Keck) for further in-depth and complementary spectroscopic studies (lack of such detailed studies has been a limitation to our understanding of planetary atmospheres). Furthermore, our development of high-precision ground-based techniques will pave the way for future follow-ups of the TESS mission that will find hundreds of nearby exoplanets. Our measurements of planetary emission spectra could assist initial target prioritization for the JWST mission. The experience and lessons learned from our observations and technical development can also benefit future analysis of similar space observations.

1.6 Management Description

1.6.1 Work Plan, project timeline and milestones

The proposed research will represent a major part of the effort of Dr. Ming Zhao as a postdoctoral researcher at PSU, and a substantial part of the effort of a Graduate Student at Caltech (Joseph O'Rourke) under Co-I Knutson's supervision. They will both be working in close collaboration with the PI and all Co-Is. In Table 1 we summarize our project timeline and milestones.

Table 1: Project Timeline and Milestones

Date	Principal Activities	Yearly Milestone
Year 1	• New multi-band observations with diffuser-assisted photometry at Palomar • Implementing the diffuser technique for Magellan/FourStar, working on corresponding pipeline • Modeling of new secondary eclipse data.	• Publish the new high precision photometry technique • Publish new multi-band results and model, combining *Spitzer* data
Year 2	• Continue multi-band observations with Palomar • Continue Magellan observations • Modeling of new secondary eclipse data, conduct comparative studies of hot Jupiter atmopsheres	• Publish new results from both Palomar and Megallan
Year 3	• Finish additional observations of planetary atmospheres at Magellan and Palomar • Modeling new secondary eclipse data • Further comparative studies of exoplanet atmospheres	• Publish additional results from Palomar and Magellan • Atmospheric modeling study of ensemble

1.6.2 Personnel and resposibilities

Ming Zhao, co-I/science-PI, has extensive experience in observation, data calibration and analysis of transiting planets. He led/participated the efforts that successfully detected secondary eclipses from 9 hot Jupiters at Palomar and MDM Observatories, and led the effort that significantly improved the guiding precision of Palomar/WIRC. Dr. Zhao is currently working closely with Co-I Kuntson and PI Wright on the new diffuser-assisted photometry. He will take the primary role in planning and carrying-out the observations and data analysis of this program, including Palomar/WIRC and Magellan/FourStar observations. As the science PI, he will be in charge of the scientific direction of the proposed work, and work closely with the PI, co-Is, and collaborator.

Jason Wright, administrative PI, has extensive experience in detection and characterization of exoplanets, and corresponding statistical studies. Prof. Wright will work closely with science-PI Zhao and oversee all aspects of this program. He will also be responsible for the overall direction of the effort and use of funds.

Heather Knutson, co-I, has extensive experience in detection and characterization of exoplanetary atmospheres and statistical studies. Prof. Knutson has led several *Spitzer* and *HST* programs to measure both the emission and transmission spectra of exoplanets. She is also leading the new diffuser-assisted photometry technique that will be used in this study. Prof. Knutson, together with a Caltech graduate student, will propose for observing time with Palomar/WIRC, and help with the planning and analysis of Palomar observations from Caltech. She will also coordinate complementary observations from other facilities, particularly the Spitzer Space Telescope, for this study.

Travis Barman, co-I, is co-developer of the PHOENIX model atmosphere code and leads the effort to maintain and improve its ability to model extrasolar planetary atmospheres. Barman has been modeling the atmospheres of extrasolar planets for more than a decade and has extensive experience with line-by-line radiative transfer, opacities, and chemical equilibrium calculations. Barman is also the lead developer of the Astrophysical Chemical Equilibrium Solver (ACES, used by PHOENIX). Dr. Barman will calculate a variety of models tailored for all targets observed as part of this proposal.

John Monnier, collaborator, has extensive experience in observational techniques, data analysis, and instrumentation. He has led many PI instruments and has been offering advice for implementing the diffuser technique. Prof. Monnier has also worked with Science-PI Zhao on MDM and Magellan secondary eclipse observations. Prof. Monnier will continue his collaboration with Zhao, utilizing the facilities from the University of Michigan – the Magellan Observatory in Chile, to measure the secondary eclipses of exoplanets using diffuser-assisted broadband photometry. He will propose for observing time with UM facilities, participate in planning and observations.

Caltech Graduate Student, Joseph O'Rourke, will participate in the Palomar observations and data analysis with the advice of Prof. Knutson at Caltech. O'Rourke has already worked on reduction and analysis of the WASP-48b observations from both WIRC and *Spitzer* (see Figure 5, O'Rourke et al. 2013, in prep.). He will also be working on available *Spitzer* results with Prof. Knutson to combine with the WIRC observations.

2

References

Agol, E., Cowan, N. B., Knutson, H. A., et al. 2010, ApJ, 721, 1861, "The climate of HD 189733b from fourteen transits and eclipses measured by Spitzer"

Anderson, D. R., et al. 2010, A&A, 513, L3, "H-band thermal emission from the 19-h period planet WASP-19b"

Anderson, D. R., Smith, A. M. S., Lanotte, A. A., et al. 2011, MNRAS, 416, 2108, "Thermal emission at 4.5 and 8 ?m of WASP?17b, an extremely large planet in a slightly eccentric orbit"

Anderson, D. R., Collier Cameron, A., Gillon, M., et al. 2012, MNRAS, 422, 1988, "WASP-44b, WASP-45b and WASP-46b: three short?period, transiting extrasolar planets"

Alonso, R., Deeg, H. J., Kabath, P., & Rabus, M. 2010, AJ, 139, 1481, "Ground-based Near-infrared Observations of the Secondary Eclipse of CoRoT-2b"

Alsubai, K. A., Parley, N. R., Bramich, D. M., et al. 2011, MNRAS, 417, 709, "Qatar-1b: a hot Jupiter orbiting a metal?rich K dwarf star"

Ballerini, P., Micela, G., Lanza, A. F., & Pagano, I. 2012, A&A, 539, A140, "Multiwavelength flux variations induced by stellar magnetic activity: effects on planetary transits"

Batygin, K., Stevenson, D. J., & Bodenheimer, P. H. 2011, ApJ, 738, 1, "Evolution of Ohmically Heated Hot Jupiters"

Batygin, K., & Stevenson, D. J. 2010, ApJ, 714, L238, "Inflating Hot Jupiters with ohmic dissipation"

Barman, T. S. 2008, ApJ, 676, L61, "On the presence of water and global circulation in the transiting planet HD 189733b"

Barman, T. S., Hauschildt, P. H., & Allard, F. 2005, ApJ, 632, 1132, "Phase-dependent properties of extrasolar planet atmospheres"

Barman, T. S., Macintosh, B., Konopacky, Q. M., & Marois, C. 2011, ApJ, 735, L39, "The Young Planet-mass Object 2M1207b: a cool, cloudy, and methane-poor atmosphere"

Bean, J. L., Désert, J.-M., Safahrt, A., et al. 2013, arXiv:1303.1094, "Ground-based Transit Spectroscopy of the Hot-Jupiter WASP-19b in the Near-Infrared"

Blecic, J., Harrington, J., Madhusudhan, N., et al. 2013, arXiv:1302.7003, "Spitzer observations of the thermal emission from WASP-43b"

Burrows, A., Budaj, J., & Hubeny, I. 2008, ApJ, 678, 1436, "Theoretical spectra and light curves of close-in extrasolar giant planets and comparison with data"

Cáceres, C., et al. 2011, A&A, 530, A5, "A ground-based K S-band detection of the thermal emission from the transiting exoplanet WASP-4b"

Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. 2000, ApJ, 529, L45, "Detection of planetary transits across a Sun-like star"

Charbonneau, D., Brown, T. M., Noyes, R. W., & Gilliland, R. L. 2002, ApJ, 568, 377, "Detection of an extrasolar planet atmosphere"

Charbonneau, D., Allen, et al. 2005, ApJ, 626, 523, "Detection of thermal emission from an extrasolar planet"

Charbonneau, D., et al. 2008, ApJ, 686, 1341, "The broadband infrared emission spectrum of the exoplanet HD 189733b"

Crossfield, I. J. M., Barman, T., & Hansen, B. M. S. 2011, ApJ, 736, 132, "High-resolution, Differential, Near-infrared Transmission Spectroscopy of GJ 1214b"

Crossfield, I. J. M., Barman, T., Hansen, B. M. S., Tanaka, I., & Kodama, T. 2012, ApJ, 760, 140, "Re-evaluating WASP-12b: Strong Emission at 2.315 ?m, Deeper Occultations, and an Isothermal Atmosphere"

Colón, K. D., Ford, E. B., Lee, B., Mahadevan, S., & Blake, C. H. 2010, MNRAS, 408, 1494, "Characterizing transiting extrasolar planets with narrow?band photometry and GTC/OSIRIS"

Cowan, N. B., Robinson, T., Livengood, T. A., et al. 2011, ApJ, 731, 76

Cowan, N. B., & Agol, E. 2011, ApJ, 729, 54, "The statistics of albedo and heat recirculation on hot exoplanets"

Croll, B., Albert, L., Lafreniere, D., Jayawardhana, R., & Fortney, J. J. 2010, ApJ, 717, 1084, "Near-infrared thermal emission from the Hot Jupiter TrES-2b: ground-based detection of the secondary eclipse"

Croll, B., Jayawardhana, R., Fortney, J. J., Lafrenière, D., & Albert, L. 2010, ApJ, 718, 920, "Near-infrared thermal emission from TrES-3b: A Ks-band detection and an H-band upper limit on the depth of the secondary eclipse"

Croll, B., Lafreniere, D., Albert, L., Jayawardhana, R., Fortney, J. J., & Murray, N. 2011, AJ, 141, 30, "Near-infrared Thermal Emission from WASP-12b: Detections of the Secondary Eclipse in Ks, H, and J"

Deming, D., Harrington, J., Seager, S., & Richardson, L. J. 2006, ApJ, 644, 560, "Strong infrared emission from the extrasolar planet HD 189733b"

Deming, D., Seager, S., Richardson, L. J., & Harrington, J. 2005, Nature, 434, 740, "Infrared radiation from an extrasolar planet"

Deming, D., Harrington, J., Laughlin, G., et al. 2007, ApJ, 667, L199, "Spitzer transit and secondary eclipse photometry of GJ 436b"

Deming, D., Fraine, J. D., Sada, P. V., et al. 2012, ApJ, 754, 106, "Infrared Eclipses of the Strongly Irradiated Planet WASP-33b, and Oscillations of Its Host Star"

Demory, B.-O., Gillon, M., Seager, S., et al. 2012, ApJ, 751, L28, "Detection of Thermal Emission from a Super-Earth"

Fortney, J. J., Lodders, K., Marley, M. S., & Freedman, R. S. 2008, ApJ, 678, 1419, "A unified theory for the atmospheres of the hot and very hot Jupiters: two classes of irradiated atmospheres"

Gillon, M., Demory, B.-O., Triaud, A. H. M. J., et al. 2009, A&A, 506, 359, "VLT transit and occultation photometry for the bloated planet CoRoT-1b"

Hubeny, I., Burrows, A., & Sudarsky, D. 2003, ApJ, 594, 1011, "A possible bifurcation in atmospheres of strongly irradiated stars and planets"

Jensen, A. G., Redfield, S., Endl, M., et al. 2012, arXiv:1203.4484, “A Detection of H? in an Exoplanetary Exosphere”

Knutson, H. A., Charbonneau, D., Allen, L. E., et al. 2007, Nature, 447, 183, “A map of the daynight contrast of the extrasolar planet HD 189733b”

Knutson, H. A., Charbonneau, D., Allen, L. E., Burrows, A., & Megeath, S. T. 2008, ApJ, 673, 526, “The 3.6-8.0 μm Broadband Emission Spectrum of HD 209458b: Evidence for an Atmospheric Temperature Inversion”

Knutson, H. A., Charbonneau, D., Cowan, N. B., et al. 2009, ApJ, 690, 822, “Multiwavelength constraints on the day-night circulation patterns of HD 189733b”

Knutson, H. A., Howard, A. W., & Isaacson, H. 2010, ApJ, 720, 1569, “A correlation between stellar activity and hot Jupiter emission spectra”

Knutson, H. A., Madhusudhan, N., Cowan, N. B., et al. 2011, ApJ, 735, 27, “A spitzer transmission spectrum for the exoplanet gj 436b, evidence for stellar variability, and constraints on dayside flux variations”

Lecavelier Des Etangs, A., Ehrenreich, D., Vidal-Madjar, A., et al. 2010, A&A, 514, A72, “Evaporation of the planet HD 189733b observed in HI Lyman-α”

Léger, A., et al. 2009, A&A, 506, 287, “Transiting exoplanets from the CoRoT space mission”

López-Morales, M., Coughlin, J. L., Sing, D. K., Burrows, A., Apai, D., Rogers, J. C., Spiegel, D. S., & Adams, E. R. 2010, ApJ, 716, L36, “Day-side z’-band Emission and Eccentricity of WASP-12b”

Madhusudhan, N., & Seager, S. 2009, ApJ, 707, 24, “A temperature and abundance retrieval method for exoplanet atmospheres”

Madhusudhan, N., & Seager, S. 2010, ApJ, 725, 261, “On the Inference of Thermal Inversions in Hot Jupiter Atmospheres”

Madhusudhan, N., et al. 2011, Nature, 469, 64, “A high C/O ratio and weak thermal inversion in the atmosphere of exoplanet WASP-12b”

Madhusudhan, N., Mousis, O., Johnson, T. V., & Lunine, J. I. 2011, ApJ, 743, 191, ”Carbon-rich Giant Planets: Atmospheric Chemistry, Thermal Inversions, Spectra, and Formation Conditions”

Moses, J. I., Visscher, C., Fortney, J. J., et al. 2011, ApJ, 737, 15, “Disequilibrium carbon, oxygen, and nitrogen chemistry in the atmospheres of HD 189733b and HD 209458b”

Öberg, K. I., Murray-Clay, R., & Bergin, E. A. 2011, ApJ, 743, L16, “The effects of snowlines on C/O in planetary atmospheres”

Perna, R., Heng, K., & Pont, F. 2012, ApJ, 751, 59, “The Effects of Irradiation on Hot Jovian Atmospheres: Heat Redistribution and Energy Dissipation”

Rauscher, E., & Menou, K. 2013, ApJ, 764, 103, “Three-Dimensional Atmospheric Circulation Models of HD 189733b and HD 209458b with Consistent Magnetic Drag and Ohmic Dissipation”

Redfield, S., Endl, M., Cochran, W. D., & Koesterke, L. 2008, ApJ, 673, L87, “Sodium absorption from the exoplanetary atmosphere of HD 189733b detected in the optical transmission spectrum”

Rogers, J. C., Apai, D., López-Morales, M., Sing, D. K., & Burrows, A. 2009, ApJ, 707, 1707, “Ks-band detection of thermal emission and color constraints to CoRoT1b: A lowalbedo planet with inefficient atmospheric energy redistribution and a temperature inversion”

Seager, S., & Deming, D. 2010, ARA&A, 48, 631, "Exoplanet atmospheres"

Sing, D. K. & López-Morales, M. 2009, A&A, 493, L31, "Ground-based secondary eclipse detection of the very-hot Jupiter OGLE-TR-56b"

Sing, D. K., Désert, J.-M., Fortney, J. J., et al. 2011, A&A, 527, A73, "Gran Telescopio Canarias OSIRIS transiting exoplanet atmospheric survey: detection of potassium in XO-2b from narrowband spectrophotometry"

Smith, M. D. 1998, *Icarus*, 132, 176, "Estimation of a length scale to use with the quench level approximation for obtaining chemical abundances"

Spiegel, D. S., Silverio, K., & Burrows, A. 2009, ApJ, 699, 1487, "Can TiO Explain Thermal Inversions in the Upper Atmospheres of Irradiated Giant Planets?"

Spiegel, D. S. and Burrows, A. 2013, arXiv:1303.0293 [astro-ph.EP], "Thermal Processes Governing Hot-Jupiter Radii"

Swain, M. R., Vasisht, G., Tinetti, G., Bouwman, J., Chen, P., Yung, Y., Deming, D., & Deroo, P. 2009, ApJ, 690, L114, "Molecular signatures in the near-infrared dayside spectrum of HD 189733b"

Swain, M. R., et al. 2009, ApJ, 704, 1616, "Water, methane, and carbon dioxide present in the dayside spectrum of the exoplanet HD 209458b"

Swain, M. R., Vasisht, G., & Tinetti, G. 2008, Nature, 452, 329, "The presence of methane in the atmosphere of an extrasolar planet"

Swain, M. R., Deroo, P., Griffith, C. A., et al. 2010, Nature, 463, 637, "A ground-based near-infrared emission spectrum of the exoplanet HD 189733b"

Wang, W., Boekel, R., Madhusudhan, N., et al. 2013, arXiv:1305.1643, "Ground-based detections of thermal emission from the dense hot Jupiter WASP-43b in H and Ks-bands"

Zahnle, K., Marley, M. S., Freedman, R. S., Lodders, K., & Fortney, J. J. 2009, ApJ, 701, L20, "Atmospheric sulfur photochemistry on hot Jupiters"

Zhao, M., Monnier, J. D., Swain, M. R., Barman, T., & Hinkley, S. 2012, ApJ, 744, 122, "Ground-based detections of thermal emission from CoRoT-1b and WASP-12b"

Zhao, M., Milburn, J., Barman, T., et al. 2012, ApJ, 748, L8, "Detection of K_S-band Thermal Emission from WASP-3b"