TRANSITING EXOPLANET CHARACTERIZATION BEYOND 2030: A CASE FOR OBSERVING GIANT PLANETS WITH GIANT TELESCOPES

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ABSTRACT

Observations of transiting exoplanets provides a rich quality of information to constrain the physical properties of exoplanets. Conducting these observations for a population of exoplanets will provide pivotal constraints on the planet formation process by tracing their gas phase and aerosol abundances. Emission and transmission spectroscopy of giant exoplanets is expected provide a wealth of high quality information (e.g. volatile & refractory abundances, scattering profiles, particle size distributions), and bridge the gap between hot Jupiters and Solar System planets. Because giant planets are 99% Hydrogen/Helium by volume, there chemistry and energy constraints are more easily understood because they are expected to more closely reflect primordial atmospheres, such as existed in the protoplanetary disk. If we first understand their formation, then they can act as a proxy to connect giant exoplanets with those in our Solar System. The *James Webb Space Telescope (JWST)* will undoubtedly transform our understanding of giant planet atomspheres. And yet, some physics will still remain outside of its wavelength range and precision estimates; e.g. aerosol scattering & most vibrational modes, as well as thermal emission from temperate (<300 K) Jupiters. Of the four large mission concepts currently being studied by NASA in preparation for the Astrophysics 2020 Decadal Survey, the *Large UV/Optical/IR Surveyor (LUVOIR)* and the *Origins Space Telescope (OST)* have instrumentation focused on transiting exoplanet spectroscopy. We will discuss here how their designs can constrain exoplanet atmospheres to improve our understanding of planet formation by studying giant transiting exoplanets, and building on the accomplishments of both *Hubble* and *James Webb Space Telescopes*.

1. INTRODUCTION

The concepts behind exoplanet science have been fundamental to the exploration of planets since we first began to probe beyond our own atmosphere. One of the NASA SMD's big science questions is, "Are we alone?". A more quantitative way of asking that question is "How unique are we?", which we can begin to statistically answer in the near future. A principle goal of exoplanetary characterization is to constrain the properties of these alien worlds, such as the atmospheric metallicities, abundance ratios, and thermal structures (Seager 2010a,b). With the advent of larger, more precise, and more stable technology – such as the *Spitzer*, *Hubble*, and *JWST* – we have only just begun to find a path to possibly answering more of these fundamental questions.

The theory of planet formation, as we know it today, is strongly dominated by the wealth of information that we attained from Solar System planets (Pollack et al. 1996; de Pater & Lissauer 2001). However, exoplanet milestones, particularly the discovery of the first hot Jupiters and the prevalence of planets in the 1-4 $R_\oplus$ range (i.e. super Earths & mini-Neptunes) via Kepler, forced us to confront planet formation theory (Howard et al. 2012; Fressin et al. 2013). After JWST launches, exoplanet science will have measurement precision and spectroscopic coverage similar to that of gas giant planetary science from 50 years ago (Danielson 1966).

Spectroscopy of exoplanet atmospheres has proven to be a useful probe to their formation, as well as the complex processes (e.g., aerosol production, deviations from chemical equilibrium) taking place. Exoplanet spectra have provided constraints on energy transport mechanisms, compositions, non-eqilibrium processes, and vertical thermal structure (Moses et al. 2011; **?**; Kataria et al. 2016).

Differences in the solar irradiation, dynamical histories, and local compositional gradients of the protoplanetary disk are dependent on both the distance from the star and the composition of the planetary atmosphere (Öberg et al. 2011). Amongst the vast diversity of planetary atmospheres, gas giant exoplanets – which are 99% hydrogen and helium by volume – will allow us to determine if all gas giants formed similar to those in the Solar System (see Marley et al. and Fortney et al. white papers). On the otherhand, rocky planets are expected greater diversity because they most likely have secondary atmospheres from surface/air interaction, ocean kinematics, outgassing, etc.

To understand the intricate details of planet formation, we must connect the vast diversity in the underlying exoplanet population to the Solar System. Giant transiting exoplanets provide a pivotal connection between these exoplanetary systems and our own. If we are able to understand the formation of giant exoplanets – within the context of their host systems – then we can begin to connect their formation of all planets. We will discuss here the capabilities of the Origins Space Telescope and the Large UV/Optical/IR Surveyor for understanding planet formation processes through spectroscopic observations of transiting giant planets.

2. SPECTROSCOPY OF TRANSITING EXOPLANETS

Spectroscopy of transiting exoplanets is an efficient technique that provides a wealth of high precision information about exoplanet atmospheres. By observing the planet as it either transits (passes in front of the host star) or eclipses (passes behind the host star), we can obstain relative measurements about the exoplanetary absorption or emission at a specific wavelength or wavelength range. Transit spectroscopy disperses stellar light to measure the exoplanetary absorption or emission as a function of wavelength. We can measure any wavelength variations and infer the existence of specific molecules (e.g. H_2O, CH_4, CO, CO_2, HCN, NH_3), as well as Rayleigh & Mie scattering from the atmosphere and any aerosol constituates. The abundance ratio of these molecules, such as C/O, can be used as proxy for conditions during the planet formation and evolution process (Öberg et al. 2011).

To date, the most common molecule that has been detected from our observations of exoplanets is H_2O, which is primarily the result of the facilities and instrumentation that we have used for observations. The *Hubble Space Telescope* has become the power house of exoplanet atmospheric characterization, with two leading instruments that can conduct spectroscopy for transiting planets: the Space Telescope Imaging Spectrograph (STIS) and Wide Field Camera 3 Infrared Channel (WFC3-IR). STIS observes from 0.3-1.0 μm – covering both atomic & molecular absorption and aerosol scattering. Charbonneau et al. (2002) detected the first atmospheric signal from an exoplanet using STIS transit

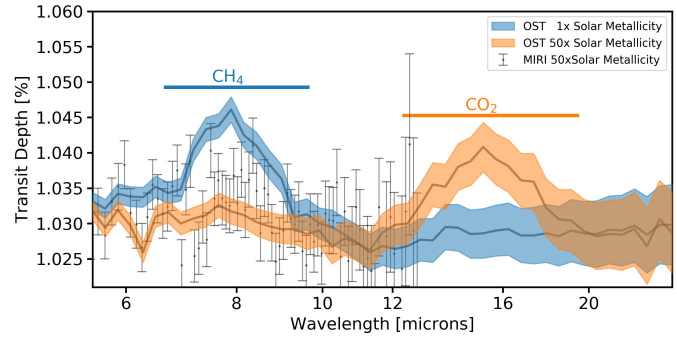

Figure 1. Example transmission spectrum of a 1000 K Jupiter analog, using ExoTransmit (Kempton et al. 2017). The blue region represents the 1-sigma boundaries for *OST* observations with a Solar composition Jupiter analog. The orange region represents the 1-sigma boundaries for *OST* observations with a 50x enriched Solar metallicity composition Jupiter analog. By comparing exoplanetary atmospheric models, we can use transit spectra like these to distinguish the molecular abundances and metallicity of the exoplanet atmosphere. Comparing a population of such transit spectra, we can begin to distinguish between giant planet formation models, and ask if giant exoplanets formed the same as our own Jupiter.

spectroscopy to detect sodium (Na) in the atmosphere of HD209458b.

Although water vapour has been detected on a range of exoplanets using *HST-WFC3* (e.g. Fraine et al. 2014; Stevenson et al. 2014; Sing et al. 2016; Wakeford et al. 2017b), the non-detection of water on GJ1214b (Kreidberg et al. 2014b) highlighted that aerosols play a large role in shaping exoplanet transmission spectra. The obscuration by aerosols was the most likely explanation for non-detection of H_2O, which is expected to be present because GJ1214b has a low measured density. This significant non-detection required modeling of cloud beyond our previously expected range, which opened a new, physical regime to explore in exoplanets (Kreidberg et al. 2014b), and to better understand aerosol production in hot, exoplanet atmospheres. Moreover, transmission and emission with WFC3 also been used to conduct spectroscopic phase-curve observations (Kreidberg et al. 2014b; Stevenson et al. 2014; Kataria et al. 2015). These spectroscopic phase-curve observations for a population of exoplanets could provide diverse constraints on the 2D atmospheric energy budget, thermal distribution, and chemical mixing properties (see Kataria et al. 2015 and Kataria et al. white paper).

3. THE NEXT STEP IN EXOPLANETARY SCIENTIFIC EVOLUTION

The soon-to-be launched *James Webb Space Telescope (JWST)* will open up a significantly larger range of wavelengths – and therefore molecules – with which to probe the atmospheres of exoplanets (see Fortney et al. white paper). JWST will conduct transmission and emission spectroscopy as well as phase-curve observations, but with much higher precision than *HST*, and at wavelengths that are sensitive to dominant oxygen-, carbon-, and nitrogen-bearing species. All four primary science instruments aboard JWST are designed with significantly better SNR and stability than existing facilities. The direct measurement wavelengths longer than *HST* is predicted to constrain the atmospheric abundances of both oxygen and carbon species (Batalha & Line 2017; Chapman et al. 2017; Schlawin et al. 2017). These measurements will add greater precision to our understanding a mass vs atmospheric metallicity, which is proxy for the initial abundances of these giant planets (**?**).

JWST will enable more precise measurements, forcing scientists to confront modeling assumptions (e.g. Barstow et al. 2015; Morley et al. 2015a; Feng et al. 2016). One of the most significant observational questions to date has become the existence, prevalence, and opacities of aerosols in the upper atmosphere of hot (>1600K) exoplanets (e.g. Wakeford & Sing 2015; Morley et al. 2015b; Parmentier et al. 2016; Wakeford et al. 2017a).

Many studies have shown that aerosols appear to be prevalent in exoplanet atmospheres (Kreidberg et al. 2014b; Wakeford et al. 2017c; Nikolov et al. 2018). Models predict that they vary in three dimensions; but the temperatures, rates, and compositions at which they form are poorly understood. Laboratory experiments have only recently begun to place constraints on exoplanet atmospheric aerosol production (Hörst et al. 2018). The experiments are conducted for temperatures <800K, leaving hot (>1000K) and very hot (>2000K) Jupiter atmospheric regimes unconstrained. Some aerosol species predicted to exist at these high-temperature (e.g. corundum (Al_2O_3) and perovskite ($CaTiO_3$)) have spectroscopic features at even longer wavelegths than JWST (Kitzmann & Heng 2018). High precision observations at long wavelength are the most viable to spectroscopically measure these high-temperature aerosols.

4. BEYOND THE HORIZON

Hubble revolutionized our understanding of exoplanet atmospheres, and JWST is predicted to change how we interpret these observations with respect to planet formation (see white paper by Fortney et al.). And yet, some physics will still remain outside of its wavelength range (0.6-11μm for transits) and precision estimates (~30ppm @ 5+μm; Greene et al. 2016). This places short wavelength aerosol scattering and long wavelenth vibrational modes, as well as thermal emission from temperate (<300 K) Jupiters, outside of the capabilities of *JWST*. The next stage in our understanding of exoplanet atmospheres will require much greater precision and more broader wavelength ranges that are currently outside of our technological reach (Greene et al. 2016). At the short wavelengths (e.g. STIS), observations are able to detect atomic absorption and aerosol scattering (Sing et al. 2016); but STIS is only able to attain precision on the order of ~100ppm, which places more significant questions out of its reach. Moreover, STIS has measured scattering albedos from exoplanet atmospheres – measuring the amount of optical energy that it absorbs and reflected (e.g. Evans et al. 2013; Bell et al. 2017). In the following sections we highlight the potential discovery space to be opened up by proposed future large mission concepts.

4.1. *Origins Space Telescope*

The Origins Space Telescope (OST) is one of the four large mission concepts currently being studied by NASA in preparation for the Astrophysics 2020 Decadal Survey. It is a future space mission concept for a 9- or 6-m aperture telescope (in its concept 1 and 2 designs, respectively), designed to capture high precision measurements of astronomical objects from 5.0 - 600 μm. The Mid-Infrared Imager, Spectrometer, and Coronagraph (MISC) on *OST* will obtain spectra of both transiting and directly imaged exoplanets. MISC will use three Si:As detectors to provide simultaneous wavelength coverage from 5-25 μm at a resolution of R = 100-300, with a precision goal of 3-5ppm (Meixner et al. 2016).

OST wavelengths will probe more than just the gas phase absorption of critical species such as CH_4, CO_2, H_2O, NH_3; it will also cover significant aerosol absorption features in giant exoplanet atmospheres (e.g. Wakeford & Sing 2015; Wakeford et al. 2017a; Kitzmann & Heng 2018). The longer wavelength capabilities of *OST* will provide the first capabilities to spectroscopically measure many of these absorption features in transiting exoplanet atmospheres. Detecting them with *OST* at longer wavelengths has the capacity to disentangle their spectral features – centered in the *OST-MISC* wavelength regime – with that of gas phase molecules.

Many aerosol species (e.g. corundum (Al_2O_3) & perovskite ($CaTiO_3$)) can only be spectroscopically detected at *OST* wavelengths – with peaks at 12 μm and 16 μm, respectively (see Figure 2; Wakeford & Sing 2015). Although vibrational modes of Enstatite ($MgSiO_3$) and forsterite (Mg_2SiO_4) have been previously measured in brown dwarf atmospheres in emission (e.g. Cushing et al. 2006) – and will likely be detected by JWST MIRI for brown dwarfs and exoplanets – because they peak in at 9 μm. These magnesium silicates are the most dominant condensate species expected to obscure hot Jupiter atmospheres at shorter wavelengths (e.g. Visscher et al. 2010; Morley et al. 2012; Wakeford et al. 2017a). *OST* will provide greater wavelength coverage and precision for these and several other species. Figure 2 shows the transmission spectrum of six of these condensate species for hot and temperate Jupiters, with three different aerosol particle sizes. We computed the transmission spectra of these aerosol species using Mie theory and the formulations outlined in Wakeford & Sing (2015) – with improved lists of condensate optical properties supplied in Kitzmann & Heng (2018). For each spectrum we assume a single cloud particle size (see Wakeford & Sing 2015), and normalize all spectra to zero at 1 micron to show the relative strength of each specral feature.

In the hotter, $T_{eq} = 1500$ K atmosphere we show the vibrational mode absorption associated with $MgSiO_3$, Al_2O_3, and $CaTiO_3$. Where *OST-MISC* and *JWST-MIRI* wavelengths overlap, the most prominent species for hotter exoplanets is still magnesium silicates. Additionally, we may also be able to measure absorption by Ti-O based species at longer wavelengths covered with *OST/MISC*, which has remained elusive in gas phase chemistry (e.g. Sing et al. 2013). Ti-O has been speculated to form clouds in the atmospheres of hotter worlds (e.g. Wakeford et al. 2017a). In the colder regime the most abundant cloud species is expected to be Na_2S (e.g. Morley et al. 2012, 2015b; Wakeford et al. 2017a) with the less abundant species as minor contributors to the overall opacity of the atmosphere. In Figure 2 we demonstrate the absorption properties of three condensates, Na_2S, KCl, and ZnS, in the low temperature regime between 500–1000 K. *OST* has the capabilities and wavelength converage to detect vibrational modes from ZnS in temperate Jupiter-analogs.

OST will also be able to detect thermal photons from temperate giant exoplanets (∼300K), whose peak emis-

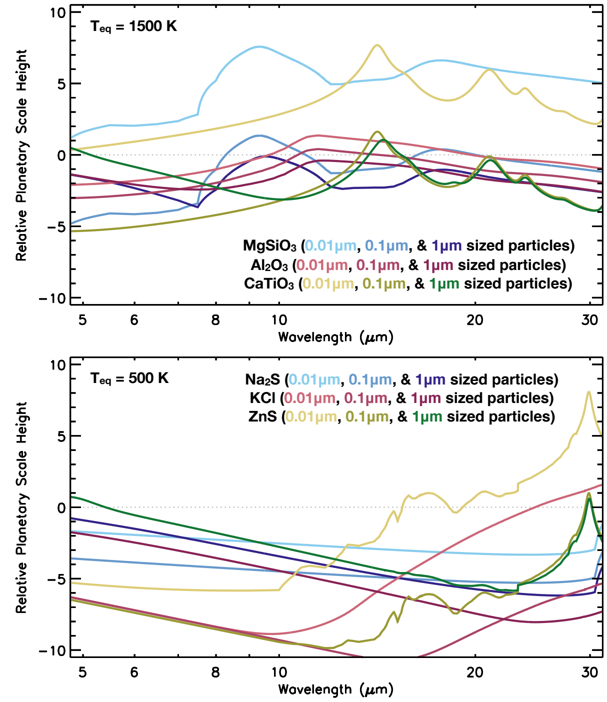

Figure 2. Transmission spectral features, represented as relative scale heights, for various condensates for hot ($T_{eq} = 1500$ K; top) and temperature ($T_{eq} = 500$ K; bottom) Jupiters. We use the methods outlined in Wakeford & Sing (2015), with the new optical properties presented in Kitzmann & Heng (2018), to compute the transmission spectrum of different aerosol species for a Jupiter-sized planet, for a Jupiter analog orbiting a Sun-like star. For each condensate, we consider three different particle sizes: 0.01, 0.1, and 1 μm. (Top) $MgSiO_3$, Al_2O_3, and $CaTiO_3$ are expected to form in the hot Jupiter ($T_{eq} = 1500$ K) regime (see Morley et al. 2012; Wakeford & Sing 2015; Wakeford et al. 2017a. (Bottom) Na_2S, KCl, and ZnS are expected to form in the temperate Jupiter ($T_{eq} = 500$ K) regime (see Morley et al. 2012, 2014, 2015b). The longer wavelength (11+μm) vibrational modes are beyond of the wavelength range supported by JWST for transiting exoplanet observations.

sion is at OST wavelengths. The direct detection of photons from temperate giant exoplanets is expected provide thermal and compositional information about these planets. $JWST$ will be able to detect photons from >300 K Jupiters, while OST can detect wavelengths senstive to Jupiters at <300 K; thus OST can build a bridge between $JWST$ observations and Solar System observations.

4.2. *Large UV/Optical/IR Surveyor*

The Large UV/Optical/IR Surveyor (LUVOIR) is also one of the Decadal Survey Large Mission Concept Studies. The $LUVOIR$ design concepts includes a large, 15- or 9-m aperture telescope (in its concept A and B designs, respectively), which is designed to capture high precision measurements of astronomical objects from 0.3 - 2.5 μm. For giant planet atmospheres, this wavelength range overlaps the current STIS and WFC3 instrumentation aboard HST, but with much better precision (Kreidberg et al. 2014b; Bolcar et al. 2016). It has the capacity to inform an order of magnitude greater knowledge of atomic abundances and aerosol scattering. STIS wavelengths (<1μm) cover both the Na and K atomic absorption lines; but $LUVOIR$ would open new regime of atomic and molecular absorption, such as sulfur and hydrocarbon chains (e.g. C_2H_2, C_2H_4, C_2H_6) (Zahnle et al. 2009a,b). Short wavelengths can also measure the aerosol scattering profile, which is critical to constraining the absolute (as opposed to relative) abundance of volatiles – detected at longer wavelengths (Benneke & Seager 2012, 2013; Griffith 2014).

Reflectance spectroscopy (see Figure 3) is another important probe of exoplanet atmospheric studies (see Morley et al. 2015a and Marley et al. whitepaper). The wavelength regime accessible to the $LUVOIR$ is optimal for exoplanet reflectance spectroscopy. Reflectance spectroscopy has been used in the Solar System for decades, and can detect both short wavelength molecular features and aerosol particle size distributions.

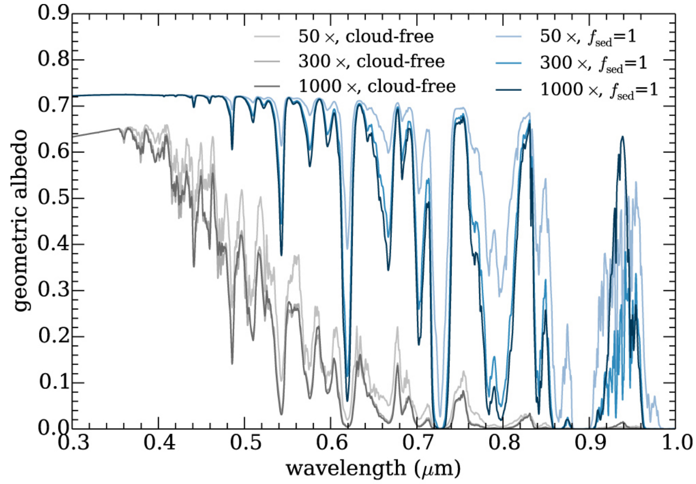

Figure 3. Figure reproduced with permission from Morley et al. (2015b). Models for spectroscopic albedo measurements for a range of cold (T∼200K), hydrogen dominated atmospheres: blue lines represent aerosol rich models; grey lines represent aerosol-free models. *LUVOIR*'s wavelength range was designed to capture are amenable to detecting both aerosol and molecular features through reflectance spectroscopic observations like those modeled here.

5. THE CASE FOR OBSERVING GIANT PLANETS WITH GIANT TELESCOPES

To greater understand the planet formation process, we should observe a population of giant exoplanets and infer from each measurement the conditions under which they were formed (Wakeford et al. 2017b; Thorngren et al. 2016). Many obstacles have interfered with our ability to gather deeper understanding of these atmospheres; and we are now at the precipice for disentangling those obstacles with new technology.

Over the last five years, opaque aerosols in the atmospheres of exoplanets have obscured the underlying molecular abundances (Kreidberg et al. 2014b). We now assume that most planets have some version of obscuring aerosols, which have inhibited our NIR transmission spectral inferences (Sing et al. 2016). Understanding the origins of these opaque layers at a range of atmospheric temperatures is a critical step forward in connected the observations of hot Jupiters to our Solar System. In the near future, we hope to infer the significance of such layers with the *James Webb Space Telescope*; we may even be able to measure their vibrational modes in the hottest Jupiters (>1600 K).

Of the four large mission concepts currently being studied by NASA in preparation for the Astrophysics 2020 Decadal Survey, the *Large UV/Optical/IR Surveyor (LUVOIR)* and the *Origins Space Telescope (OST)* have instrumentation focused on transiting exoplanet spectroscopy. Long wavelength (>10μm) emissions spectra, by OST, of colder giant planets (<300 K) would connect $JWST$ observations of giant exoplanets (>300 K) with our Solar System. Transmission spectroscopy at OST wavelengths are likely to measure vibrational modes from both refractory and soot (hydrocarbon) molecules that may be forming these obscuring aerosol layers (see Fortney et al. white paper). Short wavelength transit spectroscopy observations should be able to constrain abundances of both atomic and volatile features. Although thermal emission spectroscopy would likely be unavailable to future short wavelength missions, reflectance and transmission spectroscopy should still be able to constrain molecular and soot abundances, as well as constain the particle size distributions thereof (Morley et al. 2015b).

OST and *LUVOIR* are both designed to address those questions that we ask ourselves today. It is the yet unknown questions that the *James Webb Space Telescope* with form that these telescpes must address.

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