Simulating Haze Particles in a H_2-Rich Exoplanet Atmosphere with High Temperature Discharge Experiments.

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Introduction: During the transit of an exoplanet in front of its host star, photons of different wavelengths travel through the exoplanet atmosphere, and the incident starlight is filtered depending on the atmospheric absorbers present present. At a sufficient depth, the atmosphere will appear opaque at some wavelengths and more transparent at others. This wavelength-dependent depth in the starlight flux is called the transmission spectrum, and includes absorption features due to the planet's atmosphere [1]. These absorption features characterize the species present such as H_2O, CH_4, N_2, CO, etc., revealing important information about chemical composition, helping to constrain atmospheric scale height and temperature, and providing key inputs to photochemical and dynamical models at different altitudes.

Haze and/or cloud particles can present an obstacle to obtaining a high resolution transmission spectrum. Transmission spectroscopy is particularly sensitive to the atmospheric composition at stratosphere pressure (~10 – 100 mbar), but cloud particles and high-altitude hazes can mask atmospheric absorption features [2]. In fact, haze particles can diminish the incident starlight by scattering and absorbing a major portion of star flux, and consequently, the transmission spectrum will be flat or nearly flat with few molecular features available to characterize the atmosphere. As an example, Figure 1 (from ref. [3]) shows the recorded flat spectrum of GJ436b (a warm Neptune). The most likely explanation for the flat spectrum is the presence of clouds or photochemical hazes [3]. Transit spectra have revealed absorption signatures due to Na and K in the visible in a couple of hot Jupiters, and H_2O and CO have been detected in the IR. But the most consistent feature observed in transit spectra is a flat or nearly flat absorption spectrum from the mid-IR into the visible.

Here, we use an AC plasma discharge tube in a furnace (Fig. 2) to simulate haze production in a warm-Jupiter atmosphere [4]. We used an equal H_2/He gas mixture together with ~10% of a mixture of CH_4, N_2, and H_2S in the ratios 2:1:1. Runs were done with and without H_2O vaspor; with H_2O present, C:O in the mixture was 0.5 (i.e. solar C/O). The gases were mixed to a total pressure ~100 mbar in a glass manifold. Then, with the discharge tube heated to ~ 800K, the manifold gas was flowed into the discharge tube. Tungsten electrodes were used to generate 60Hz plasma discharge at a votage of several kV with an arc nearly spanning the width of the furnace (~15 cm). Runs were ~ 1 hour in duration.

Preliminary Results: Thin films of particulates formed in the hot discharge are collected on fused quartz plates positioned beneath the tips of the electrodes. An example from one run is shown in Fig. 3. The main goals of this experiment are to measure the optical properties of the thin film, and also to understand the elemental abundance and the chemical structure of the thin film deposits. Since we apply temperature and pressure ranges similar to the stratosphere of warm Jupiters/Neptunes, albeit with enhanced trace gas fraction, we assume that our thin films are representative of hazes produced by charged particle impact in the exoplanet upper atmosphere. Using spectroscopic ellipsometry, the complex refractive index has been measured and calculated for one run (Fig. 4). The complex refractive index, composed of real and imaginary parts, n and k, is needed to calculate the extinction of starlight from atmospheric haze particles. The *n* and *k* values for our thin film can be compared with refractive index data for graphite (C), sulfur (S_8), and tungten (W) (Fig. 5). Chemical composition measurements of the thin films are in progress. Model transmission spectra calculations, including Mie-scattering from haze particles with the optical constants of our thin fiim, are also in progress.

Conclusion and Implication: Because haze and/or cloud particles appear to be the main reason for scattering the incident starlight to produce flat transit spectra, laboratory simulation experiments of the type reported here can be useful to understanding particle production in exoplanet atmospheres. Similar experiments were performed by Khare et al. [5] on N_2/CH_4 mixtures to simulate Titan well known haze, yielding a rich array of particles known as 'tholins'. In addition, benzene and other complex heavy hydrocarbons has been observed and modeled in Jupiter [6,7]. Most previous plasma discharge experiments did not include H_2O [8]. In our experiments, we used ~16% of water vapor and we still find particle production. This is an important result since we expect warm Jupiters/Neptunes to have a high fraction (solar or above) of H_2O in their stratospheres. Even in the presence of substantial water, there is still the possibility of haze particle formation. Spectroscoic analysis and experimental work is in progress for determination of the chemical properties. Particle production experiments in atmospheres of other compositions are planned.

References: [1] Madhusudhan N. et al. (2014) *Protostars and Planets VI, University of Arizona Press*, 914, 739. [2] Marley M. S. et al. (2013) *University of Arizona Press*, 610, 367. [3] Knutson, H. A. et al. (2014) *Nature*, 505, 66. [4] GharibNezhad E., Lyons J. R., and Wright D. P. (2015) *American Physical Society-4CS* Log#4CF15-2015-000118. [5] Khare B. N. et al. (1984) *Adv. Space Res.* 4, 59. [6] Wong, A.-S. et al. (2003) *Geophys. Res. Lett.*, 30, 1447. [7] McDonald G. D. et al. (1992) *Icarus* 99, 131. [8] Imanaka, H. et al. (2015) *American Astronomical Society, DPS meeting* #47, id.#416.18.

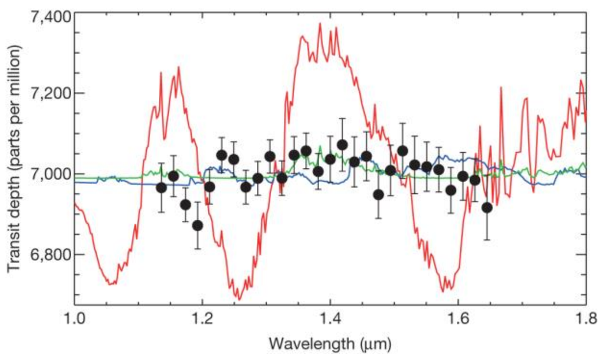

Fig. 1. Example of a flat transmission spectrum seen for GJ436b. Black circles represent the recorded transit depth with 1σ standard deviation measurement errors. Red, blue and Green lines are three models for cloud-free, hydrogen-poor, and solar-metallicity model, respectively. (Figure from Knutson et al. [3]).

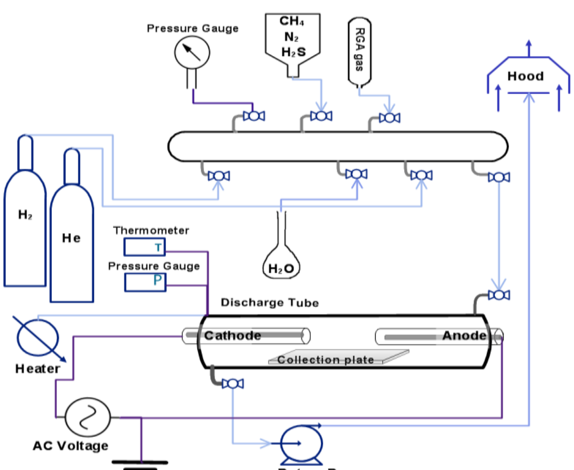

Fig 2. Using an AC plasma discharge tube, particle production in a warm-Jupiter exoplanet atmosphere is simulated. The C/O ratio in this experiment is ~0.5. When the temperature of the discharge tube is ~ 800K, the total mixture gas from the manifold is transferred to the tube. A plasma arc is formed at several kV, and is maintained for ~ 1 hour.

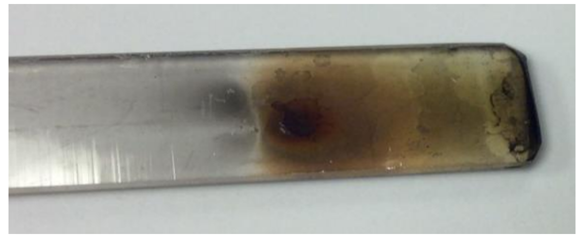

Fig 3. Thin film deposition on a fused quartz placed beneath one electrode. Dimensions 15 cm × 3 cm.

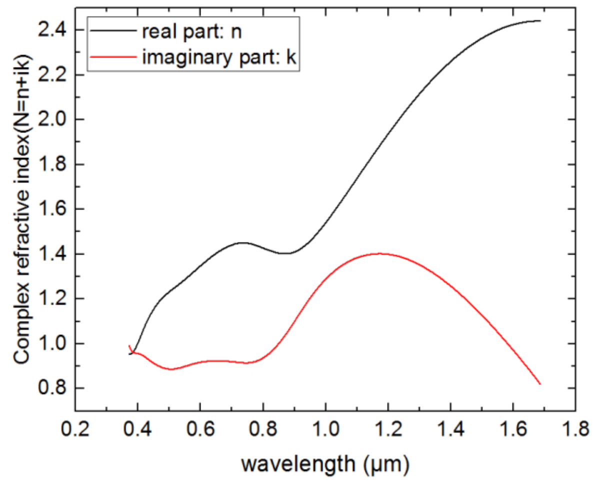

Fig. 4. Thin film deposition refractive indices n, k. The real and imaginary part of the refractive index have been measured by spectroscopic ellipsometry in the lab of Dr. Zachary Holman in at Arizona State University, with the assistance of Dr. Mathieu Boccard.

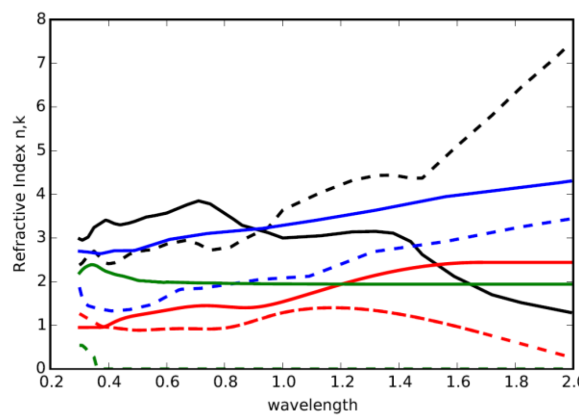

Fig. 5. Using spectroscopic ellipsometry, the real (solid) and imaginary (dashed) part of the refractive index of our collected thin film (red) are compared with graphite (blue), tungsten (black), and sulfur S_8 (green).