National Aeronautics and Space Administration

FY23 Strategic Initiatives Research and Technology Development (SRTD)

Defining Spectral Characterization for Habitable Exoplanets

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Strategic Focus Area: Developing tools for scientific optimization of missions | **Strategic Initiative Leader:** Charles Lawrence

Objectives: This study will achieve the following specific objectives, and they are prioritized based on the perceived impact on the architecture trade of the astrophysics flagship mission and the technology maturation program that will soon ramp up. We will first determine the wavelength range and resolution (particularly in the UV and IR) to distinguish and characterize plausible scenarios of terrestrial exoplanets. Based on this, we will apply the retrieval framework to determine the wavelength range and resolution to distinguish gas-rich planets from terrestrial planets, particularly when the mass is unknown, and the requirements to detect and measure the abundances of biosignature gases. We will also run N-body simulations to trace late-stage planet formation and gas accretion, and explore the range of plausible initial distributions of planetesimals with ~100 simulations. We will compare the simulated planetary systems to known planet populations and derive predictions on the planet parameters that would be the most sensitive indicators of whether the planets have massive H_2 atmospheres. Lastly, we will study the impact of non-uniform cloud coverage on spectral retrieval and the requirements to measure land/ocean/cloud fractions for some of the more favorable targets.

Background: The next several years are potentially transformative for exoplanet exploration, with JWST in operation and decisions to be made for the technology maturation programs to enable a 6-meter-class space telescope capable of high-contrast imaging (now referred to as the "Habitable World Observatory", or HWO). The Astro2020 decadal survey demanded that HWO should yield "a robust sample of ~25 atmospheric spectra of potentially habitable exoplanets," but it did not specify what an adequate "atmospheric spectrum" or "potentially habitable exoplanets" would entail. These two science uncertainties, left for the scientific community to decide, are of paramount importance as they bear upon the trade and selection of the architecture of the flagship mission, and also on the technology maturation programs that will ramp up in ~FY25. For example, whether HWO would have spectroscopic capabilities in UV or IR, the wavelength cutoffs, and whether HWO would include single or multiple parallel coronagraphs or a starshade, all hinge on the measurement requirements for identifying and characterizing potentially habitable exoplanets. This project will delineate the measurement requirements for identifying and characterizing potentially habitable exoplanets, and thus impact the trade and selection of the architecture of the flagship mission.

Approach and Results: We have completed spectral retrieval simulations for planets like Proterozoic Earth, exploring varied measurement scenarios with/without spectral coverage in UV and NIR. These simulations have demonstrated that the mixing ratio of O_3 could be sufficiently constrained with a wavelength coverage that includes 0.25 – 0.4 μm (Fig. 1a). With a modest spectral resolution of R=7 in this band, SO_2 or H_2S are unlikely to interfere with the detection of O_3. We also confirm the previously published results that the NIR coverage is necessary to constrain the cloud properties and the mixing ratio of H_2O. We have published this result on Astronomical Journal and presented it at the AAS winter meeting.

For determining the impact of the uncertainty of planetary mass, we have developed and implemented to ExoREL-R a new 2D prior function for the planetary mass and radius, developed a realistic noise spectrum model for the speckle-dominated regime and the shot-noise-dominated regime, and improved the numerical scheme to speed up the evaluation of the model while maintaining accuracy. With retrieval simulations using an Earth-like spectrum, we have found that the planetary mass can be constrained by the spectra, and the retrieved atmospheric abundances are insensitive to the prior knowledge of the planetary mass (Fig. 1b). Given the potential far-reaching implication of this finding, we have relaxed model assumptions, particularly the parameterization of cloud density and particle size, and found the basic takeaway remains while the planetary mass constraints become looser. We will expand the retrieval simulations to planets like Archean Earth and planets having CO_2-dominated atmospheres.

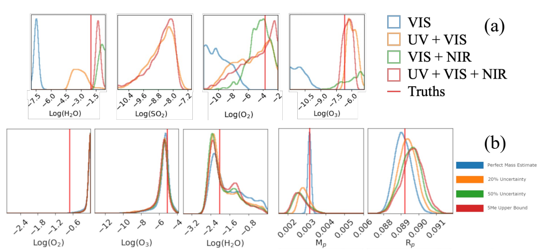

Fig. 1: (a) ExoREL-R applied to planets like Proterozoic Earth, showing constraints on the atmospheric abundances for different wavelength coverage. The mixing ratio of O_3 is constrained only when the wavelength coverage includes UV, and the mixing ratio of H_2O is constrained only when the wavelength coverage includes NIR. (b) Impact of varied prior constraints of the planetary mass. These retrieval simulations using an Earth-like spectrum show that the planetary mass can be constrained by the spectra, and the retrieved atmospheric abundances are insensitive to the prior knowledge of the planetary mass.

We have also completed the initial simulations of late-stage planet formation for both the pebble accretion scenario and the planetesimal accretion scenario. We have advised a summer student to derive statistical measures from previously run simulations and compare them with the *Kepler* planet population statistics. This comparison indicates that the mass concentration, one of the statistical measures, can be well matched by pebble accretion models while the orbital spacing, another statistical measure, cannot. We are running ~100 independent planet formation simulations to explore the initial mass distribution of planetesimals, with the aim to match both statistical measures.

Significance/Benefits to JPL and NASA: This study contributes to establishing the scientific baseline that defines the Habitable World Observatory, consolidating JPL's leadership in the development and eventual science programs of the future flagship mission. Specifically, we have presented the UV science cases delineated by this study at the Coronagraph Technology Roadmap Working Group, the HWO/starlight suppression workshops organized by STScI and by JPL, and other GOMAP groups and discussions. This insight provides key scientific argument for a starshade, and the short-wavelength cutoff at 0.25 um informs the choices of telescope coating. Meanwhile, preliminary results of our analysis on the planetary mass have already generated discussions in the GOMAP community as they bear upon whether extreme precision radial velocity measurements are a prerequisite of HWO.

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