National Aeronautics and Space Administration

FY24 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 project seeks to optimize the spectral characterization for habitable exoplanets for the Habitable Worlds Observatory (HWO) with coupled spectral retrievals and realistic and diverse models of terrestrial planets, and determine the measurement requirements to distinguish bona fide rocky planets from gas-rich planets with both spectral retrievals and planet formation simulations anchored by observations. In Year 2, the objectives are: (1) determine the impact of the uncertainty of planetary mass on the spectroscopic characterization of Earth-like exoplanets in the context of HWO; (2) determine the spectroscopic measurements needed to detect biosignatures including CH_4-CO-CO_2 and N_2O; (3) Test the spectral retrieval methods and derive the spectroscopic measurements needs for Earth-like planets with realistic surface and cloud scenarios; and (4) Use planet formation models to set priors for spectral characterization.

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 the size of the primary mirror, all hinge on the measurement requirements for identifying and characterizing potentially habitable exoplanets.

Approach and Results: We have published a paper on the spectroscopic requirements in UV to characterize planets like Proterozoic Earth (Damiano et al. 2023) and another paper on the impact of planet migration on the architecture of multi-planetary systems (Shariat et al. 2024). These papers summarized the key findings in Year 1, and we have worked them through the peer review process in Year 2.

We have completed the investigation of the impact of the uncertainty of planetary mass on atmospheric retrievals. With representative rocky planet scenarios guided by Earth's evolutionary history, we found that the reflected light spectra alone can result in the constraints of the planetary mass to within a factor of 2, but the retrieved atmospheric abundances can be substantially biased without the prior mass constraints. We have developed a novel prior function that connects the planetary mass and radius – there is a finite plausible range for a planet's density – and shown that, with this prior, the bulk atmospheric abundances can often be recovered correctly. We have also shown that, if the mass is known to a precision of better than 30% (presumably by extreme precision radial velocities), the atmospheric retrievals will not be impacted. We are writing a paper to summarize these results and will soon submit it AAS journals.

We have completed the investigation of the spectroscopic needs to detect biosignatures CH_4-CO-CO_2 and N_2O. We found that, due to weak spectral features and overlapping with stronger CO_2 features, it will be challenging to measure CO to rule out the false positive scenarios that CH_4 is geological rather than biological based on a planet's reflected light spectrum. We also found that N_2O will be readily detectable in the reflected light for a wide range of planetary conditions and a wavelength coverage of up to 1.4 μm. We have presented some of the results at the AAS winter meeting in January and have written a paper to summarize these results and submitted it AAS journals.

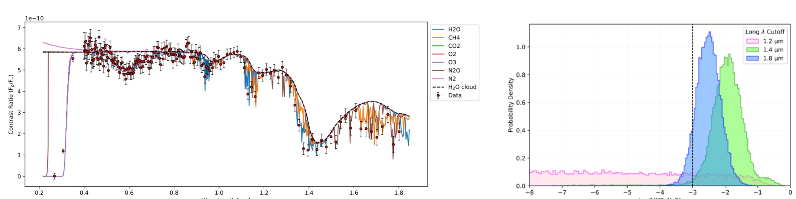

Figure: (Left) Flux contrast ratio for a Proterozoic-Earth-like exoplanet with a volume mixing ratio of N_2O of 10^{-3}. The input forward model is shown by the red circles, and the retrieval result is overlain and separated by molecule to show the individual molecular contributions. The spectrum does not have any dominating features, but absorption of O_3, H_2O, CH_4, and N_2O are evident. Posterior solution curves for the mixing ratios of N_2O for long wavelength cutoffs at 1.8 μm (blue), 1.4 μm (green), and 1.2 μm (pink). The dashed vertical line indicates the input value. A long wavelength cutoff of 1.8 and 1.4 μm results in constrained and fairly accurate posteriors, whereas a 1.2-μm cutoff leads to a non-detection of N_2O.

We are also well on the way in studying the spectroscopic needs for measuring atmospheric abundances vis-à-vis realistic surface and cloud scenarios. We have simulated Earth's reflected light spectra in 0.3-2 μm, based on a high-resolution 3D atmospheric and surface model validated extensively by terrestrial observations. We have applied ExoREL to retrieve from these spectra, and preliminary results are encouraging as we consistently detect O_2, H_2O, and O_3. However, the retrievals do not always show an N_2-dominated atmosphere, the retrieved gas abundances can have strong biases, and apparent residuals remain in the spectral fit. This suggests that the actual Earth's spectrum could provide richer information than previously thought, including wavelength-dependent surface albedo and ice versus liquid water clouds. We are writing a paper to summarize these results and will soon submit it AAS journals.

Significance/Benefits to JPL and NASA: Our study has demonstrated that detecting gases in the atmospheres of Earth-like exoplanets is largely insensitive to the prior knowledge of planetary mass, while the determination of the bulk atmospheric composition (O_2 versus N_2) would only be possible if the mass is known to the precision better than ~10%. This information quantifies the science value of measuring planetary mass and has been provided to various science working groups of the Habitable Worlds Observatory.

Our results on the biosingatures have important ramifications on the limitation of the CH_4-CO_2 biosignature for HWO and compels us to consider CO's spectral features at longer wavelengths (~4.6 μm) where the planet's light will be dominated by thermal emission rather than reflected starlight. Our demonstration of N_2O as a viable alternative biosignature gas has compelled HWO science cases written up by the Living Worlds working group.

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Publications:

Damiano, M., Hu, R., & Mennesson, B. (2023). *The Astronomical Journal*, *166*(4), 157.

Shariat, C., Hasegawa, Y., Hansen, B. M., Yu, T. Y. M., & Hu, R. (2024). *The Astrophysical Journal Letters*, *964*(1), L13.

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