National Aeronautics and Space Administration

FY24 R&TD Innovative Spontaneous Concepts (ISC)

Quantifying how uncertainties in retrieval of exoplanet atmosphere parameters depends on telescope design

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Strategic Focus Area: Innovative Spontaneous Concepts

Objectives:

A key goal of the future Habitable World Observatory (HWO) is to understand exoplanet atmospheres and to detect life signatures within them. NASA has published a list of current science and technology gaps in the development of this mission, two of which relate to the lack of models to predict retrieval uncertainties of exoplanet properties as a function of telescope design. Our objective is to use a combination of exoplanet atmosphere models, statistical analysis with probability density functions, and predictions of transmission and absorption spectra to create a framework to quantify these uncertainties

Background:

Choosing an optimal telescope design for a mission requires an assessment of how the design affects the accuracy in which science parameters can be retrieved from the data taken. Various parameters can affect this accuracy including the signal-to-noise ratio, and spatial and spectral resolutions. We have developed a method for assessing this and have demonstrated its use for observations of protoplanetary disks (Seo et al. 2024). Here we extend our method to exoplanets, with the specific aim of aiding in the development of HWO.

The uncertainties in the retrieval of scientific data from observations can be quantified using probability density functions (PDFs) (see Seo et al. 2024). The PDFs are estimated using a large number of forward Monte Carlo models covering a wide parameter space. The widths of the PDFs infer the uncertainties in the retrievals and they vary depending on the sensitivity of the telescope. This approach avoids iterative modeling localized near the solution, which is inefficient for exploring the large model space required for designing a telescope.

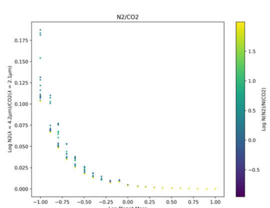

Figure 1. Relative intensities of N2 and CO2 emission as function of planet mass, indicating that the atmospheric opacity dominates the predicted emission.

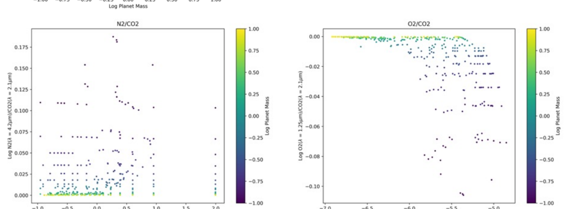

Figure 2. Comparing predicted intensities to column density ratios: (left) N_2/CO_2, (right) O_2/CO_2.

References:
Allen, M. et al. (1981) JGR, 86, 3617
Kleinbohl, A., Willacy, K., Friedson, A., Swain, M. (2018), ApJ, 862, 92
Seo, Y., Willacy, K., Bryden, G., Lis, D., Goldsmith, P., Pontoppidan, K., Thi, W.-F. (2024), ApJ, 967 131

Approach and Results:

We have constructed a number of exoplanetary atmosphere models covering planet masses from 0.1 to 10 Earth mass, and with varying compositions. For this first study we assume a solar mass star, and that the planet is located at 1 au from the star. We assume that the planets are initially a mixture of N_2 and CO_2 with the addition of water in the lower atmosphere. The fraction of N_2 ranges from 0.1 to 1. The models are run for 1 billion years and the final composition is used to generate transmission and emission spectra. We then analyze the data statistically to determine correlations between the column densities, intensities, planet mass and initial composition.

The exoplanet simulations are carried out using the Caltech/JPL photochemical/transport model, KINETICS (Allen et al. 1981) which is linked to a radiative convective equilibrium code to provide the atmospheric structure (Kleinbohl et al. 2018). From the calculated atmospheric composition the transmission spectra are modeled at three different resolving powers (R=25, 100 and 500). The derived intensities are then used to construct the PDFs and to determine trends between planetary mass, and the column densities of observable molecules (CO_2, O_2, O_3).

We find that the intensities of N_2, CO_2, O_2 and O_3 do not correlate well with their column densities. The intensities instead track the mass (Figs 1 & 2) suggesting that the dominant parameter in determining the intensity is the optical depth. We find that the PDFs (Fig. 3) provide a most probably value that is aligned to the true solution in most cases, but where the density of model points is low the most probable value misses the true solution. More models are needed to improve prediction accuracy.

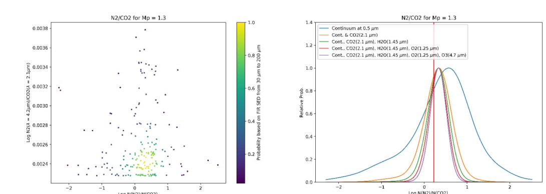

Figure 3. (left) predictions of intensities relative to column density ratios of N_2/CO_2. (right) Probability density function of N_2/CO_2 with respect to observations. The red vertical line is the true solution.

Significance of results

There are two main conclusions to be drawn from our work

1. Optical depth effects dominate the transmission spectra

We found that the transmission spectra are strongly dominated by the optical depth of the atmosphere. The atmospheric optical depth is mainly controlled by planet mass since the atmospheric mass is determined by the gravity of the planet. We found that the planet mass is tightly correlated with all the absorption/emission features of the chemical species we consider. Therefore, we may use the absorption/emission features to determine the planet mass relatively accurately, but determining other planet properties, e.g. chemical abundances, is less accurate.

2. Absorption/emission features correlate weakly with the chemical abundances.

The strengths of spectral features are mainly dominated by the total optical depth of the atmosphere (and therefore by planet mass). Chemical abundances may be weakly correlated to the absorption/emission feature strengths only when the planet mass is already known (Fig. 3). Using the PDFs between the observables and chemical abundances, we may estimate the ratios between the chemical species e.g. N_2/CO_2.

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