Information Theory and Exoplanetary Atmospheres: A New Way to Search for Life

Abstract: We applied Jensen-Shannon divergence (D_{JS}), an **information theory measure** that quantifies how effectively one probability distribution can model another, to determine the **similarity of exoplanetary transmission spectra**. We used Exo_Transmit, an open-source code for modeling planetary transmission spectra, to simulate **hot Jupiter** and **super-Earth** planets, calculating D_{JS} versus simulations of Earth, Jupiter, and hot Jupiter planets. The D_{JS} values helped **identify the types of exoplanets** in question and could pick out single-parameter changes in exoplanet simulations.

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Authors

Ian Stiehl, Dartmouth College

Sara Vannah, Dartmouth College
Marcelo Gleiser, Appleton Professor of Natural Philosophy, Dartmouth College

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Introduction

On December 25, 2021, the **James Webb Space Telescope** (JWST) hurtled into the sky to collect the next generation of astronomical data, with the first data release only a few weeks away. JWST will observe wavelengths of light that allow it to detect high redshift galaxies and **biosignatures** through transit spectroscopy measurements. We apply information theory to analyze exoplanet transmission spectra to begin **characterizing exoplanets** without input physics. Thus, this method provides an automatic way to identity Earth-like planets, circumventing disagreements on contested science about what constitutes **habitability**.

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Objective

We investigated a method that screens large numbers of **transmission spectra**, identifying different types of planets and determining whether they might be good candidates in the **search for life**.

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Methodology

We applied **Jensen-Shannon divergence** (D_{JS}), a symmetric measure of the difference in Shannon entropy (Shannon. 1948) between two probability distributions, to compare exoplanets' transmission spectra simulated with **Exo_Transmit**, an open-source code published by Kempton et al. 2017. My simulations included

- 10 hot Jupiters,
- 10 super-Earths,
- Jupiter and Jupiter variants, &
- Earth.

Some of these simulations were based on detected and confirmed exoplanets while others were not.

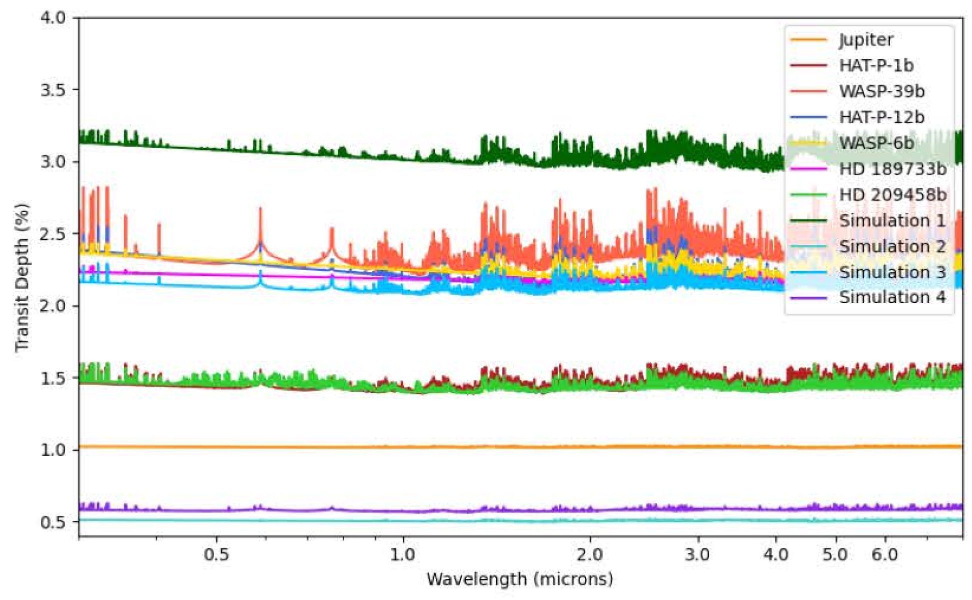

Figure 1: Example transmission spectra are shown for the 10 hot Jupiter simulations.

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Results

First, we studied how **changing a single parameter** of the Jupiter simulation altered D_{JS} outputs when compared to the original Jupiter and Earth. As seen in Fig. 2, D_{JS} remained high for all Earth comparisons as the differences between the spectra remain large. D_{JS} was **minimized** when Exo_Transmit inputs were most similar to Jupiter and increased as the inputs diverge.

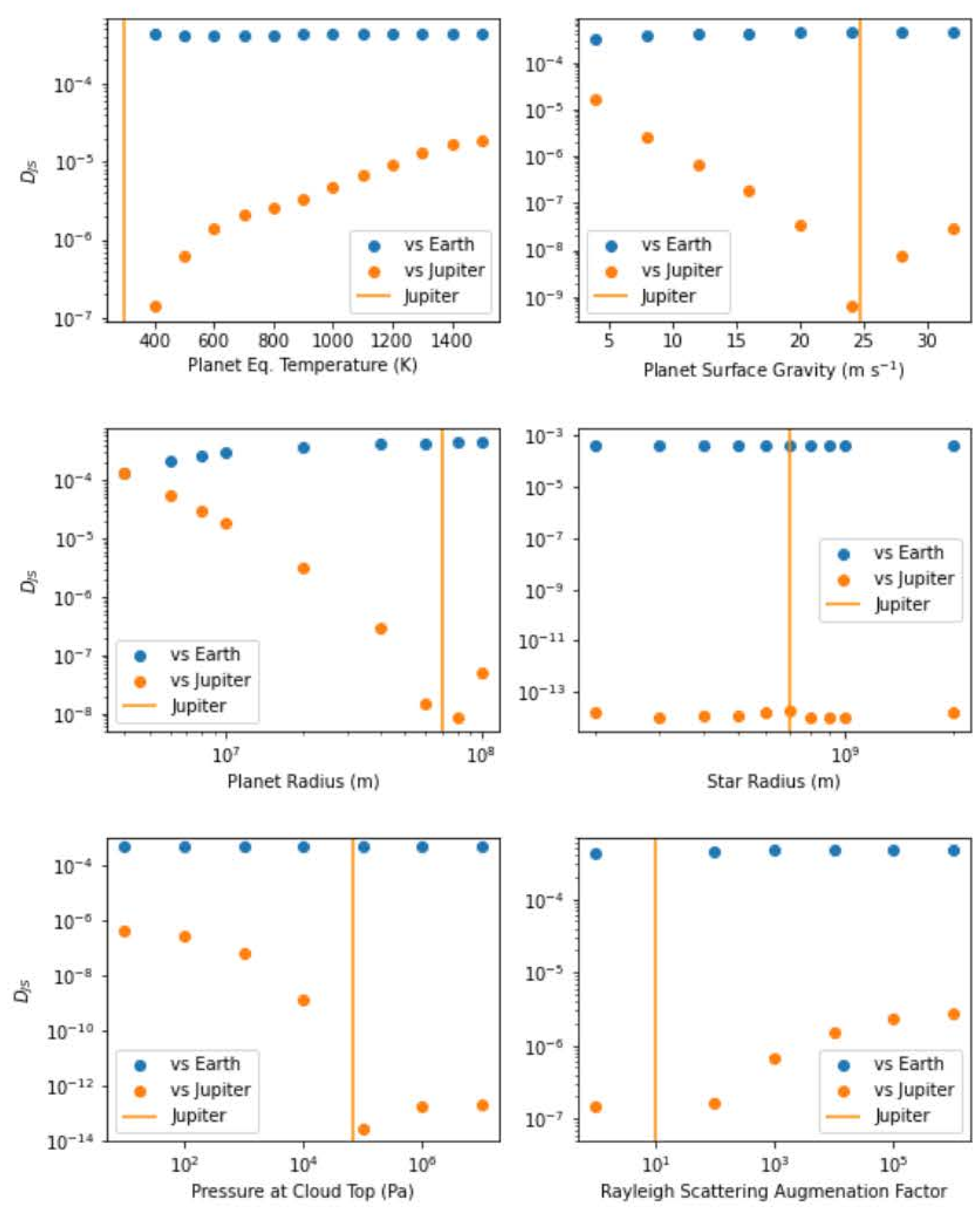

Figure 2: Single parameters of the Jupiter simulation are varied and changes in D_{JS} are plotted against those changes. Included in each plot are orange vertical lines that specify the original Jupiter input parameter.

Next, I examined the samples of 10 **hot Jupiters** and 10 **super-Earths** by measuring their D_{JS} compared to Earth, Jupiter, and a 1200 K Jupiter variant (see Fig. 3). The sample of hot Jupiters had **no overlap** between D_{JS} comparisons to Earth and comparisons to the Jupiters. By contrast, the super-Earths overlapped dramatically, largely due to a few key parameters in Exo_Transmit.

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Analysis

- D_{JS} was **sensitive** to minor changes to planetary spectra resulting from single-parameter modifications (Fig. 2)
- For the hot Jupiter spectra, D_{JS} **distinguished** between comparisons to Earth and Jupiter, creating an automatic method to classify this type of exoplanet **without input physics**
- Super-Earth spectra had overlapping D_{JS} ranges when compared to Earth and Jupiter due to opposing effects of parameters such as metallicity and temperature
- Relevant planets such as Trappist-1e and Proxima b showed reduced D_{JS} when compared to Earth versus Jupiter

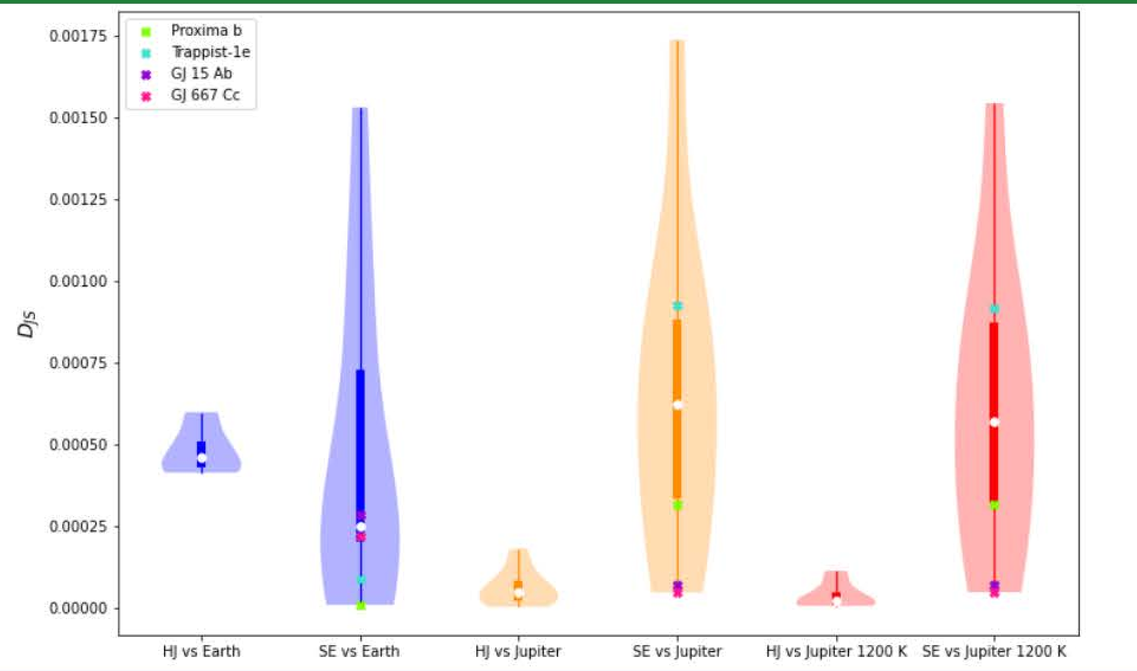

Figure 3: Both the super-Earth (SE) and hot Jupiter (HJ) D_{JS} output distributions are shown when compared to Earth, Jupiter, and 1200 K Jupiter, using violin plots. The thin lines connect the minima and maxima of each distribution, the thick line illustrates the interquartile range, and the white points represent the medians. Additionally, four color-coded X's specify the exact D_{JS} values of four chosen exoplanets.

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Conclusion

I demonstrated that D_{JS} is sensitive to **subtle patterns** in transmission spectroscopy data and can distinguish between different planet types. Reduced D_{JS} for comparisons of Earth to **Trappist-1e** directly relates to identifying habitable planets. Further work is necessary to understand how multiple altered planet parameters affect D_{JS} and upcoming work by Vannah et al. will examine how D_{JS} density can identify biosignatures.

References

Kempton et al., 2017, PASP, 129, 044402.
Shannon, 1948, BSTJ, 27, 379–423.