The Astrobiology of The TRAPPIST-1 System

Thematic Areas (Check all that apply):

☒ (Theme A) Key science themes that should be prioritized for future JWST and HST observations
☐ (Theme B) Advice on optimal timing for substantive follow-up observations and mechanisms for enabling exoplanet science with HST and/or JWST
☐ (Theme C) The appropriate scale of resources likely required to support exoplanet science with HST and/or JWST
☐ (Theme D) A specific concept for a large-scale (∼500 hours) Director's Discretionary exoplanet program to start implementation by JWST Cycle 3.

Summary: Although humans have pondered our place in the Universe for millennia, JWST is the first telescope capable of studying extrasolar terrestrial planets and initiating the search for life beyond our Solar System. It is therefore imperative that we capitalize on this unprecedented opportunity to prioritize observations of a range of terrestrial exoplanets to understand their nature, evolution and potential habitability [1]. Simulations from multiple research groups suggest that these observations will be extremely challenging, but that they have the potential to reveal the host star's impact on terrestrial planetary atmospheric retention, composition, evolution and climate as a function of distance from the star, as well as provide observational tests of the habitable zone limits [2]. JWST observations of terrestrial HZ planets will also enable the first search for biosignature gases, and planetary environmental context such as signs that abiotic processes may be operating to mimic, suppress or enhance biosignatures [3, 4]. The TRAPPIST-1 planetary system in particular provides an excellent first target for exoplanet astrobiology as its seven planets span a broad range of distances interior to, within and exterior to the habitable zone [5] and the small host star maximizes the strength of atmospheric signals. For example, simulations suggest that 6 transits of TRAPPIST-1 d and 14 transits for TRAPPIST-1 e would be sufficient to robustly detect an atmosphere and search for signs of atmospheric evolution and life. However, this number is based on the assumption that parallel community-wide efforts to mitigate stellar contamination succeed.

Anticipated Science Objectives: Studying M dwarf systems with JWST will illuminate the broader coevolution of habitable zone terrestrial planets with their parent star, advancing the Astro2020 "Worlds and Suns In Context" science goal [6] and providing unprecedented observations to address the JWST Key Science Theme on Planetary Systems and the Origin of Life. TRAPPIST-1 d and e straddle their star's inner HZ limit, and the presence and nature of their atmospheres can be used to test the location and applicability of the habitable zone concept for M dwarf planets. JWST NIRSpec transmission spectroscopy can robustly determine whether these planets have retained atmospheres, and simultaneously search for CO_2, O_2-O_2 and H_2O that may reveal past or ongoing ocean loss [1, 2]. The same data can be used to search for the relatively detectable and potentially long-lived CO_2/CH_4 disequilibrium biosignature [3, 7], and its false positive indicator, CO [8]. These observations are only possible with JWST, which can revolutionize our understanding of the impacts of M dwarf stellar evolution on the habitability of terrestrial exoplanets, and the possibility of life beyond the Solar System.

Urgency: To obtain adequate signal to noise to detect atmospheric molecules, many transits will need to be coadded over multiple cycles and to maximize the science this will need to be started as soon as possible. For biosignatures on TRAPPIST-1 e, simulations suggest 14 transits minimum are needed for robust atmospheric detection for a range of clear and cloudy atmospheres. Additionally, if flares are as frequent as preliminary data suggest, with the potential to strongly affect half of the transit observations [9], then much larger numbers of transits (e.g. 30) may be needed. This exceeds the 10 transits total available for T-1e in a given cycle and also strongly motivates parallel efforts to mitigate stellar contamination [10, 9], and using multi-transit windows wherever possible.

Risk/Feasibility: For a broad range of likely atmospheres, it seems feasible that an atmosphere could be detected and characterized. However, there is always a risk that the HZ planets do not have atmospheres, although it has been argued that that is unlikely, even if the inner planets (T-1 b and c) are airless [11].

Timeliness: With this new capability, it seems remiss to not promptly conduct *the first feasible search for signs of life in terrestrial exoplanet atmospheres!*

Cannot be accomplished in the normal GO cycle: To compensate for observations loss due to flaring, and to obtain the required signal to noise to detect and characterize the atmosphere for the TRAPPIST-1 planets, multiple cycles will be required spanning several years.

References

[1] Andrew P. Lincowski et al. "Evolved Climates and Observational Discriminants for the TRAPPIST-1 Planetary System". In: 867, 76 (Nov. 2018), p. 76. DOI: `10.3847/1538-4357/aae36a`.

[2] Jacob Lustig-Yaeger, Victoria S. Meadows, and Andrew P. Lincowski. "The Detectability and Characterization of the TRAPPIST-1 Exoplanet Atmospheres with JWST". In: 158.1, 27 (July 2019), p. 27. DOI: `10.3847/1538-3881/ab21e0`. arXiv: `1905.07070 [astro-ph.EP]`.

[3] Joshua Krissansen-Totton et al. "Detectability of Biosignatures in Anoxic Atmospheres with the James Webb Space Telescope: A TRAPPIST-1e Case Study". In: 156.3, 114 (Sept. 2018), p. 114. DOI: `10.3847/1538-3881/aad564`. arXiv: `1808.08377 [astro-ph.EP]`.

[4] V. S. Meadows, A. P. Lincowski, and J. Lustig-Yaeger. "The Feasibility of Detecting Biosignatures in the TRAPPIST-1 Planetary System with JWST". PSJ, accepted. 2023.

[5] Michaël Gillon et al. "Seven temperate terrestrial planets around the nearby ultracool dwarf star TRAPPIST-1". In: *Nature* 542.7642 (2017), pp. 456–460. ISSN: 0028-0836. DOI: `10.1038/nature21360`. URL: `http://www.nature.com/doifinder/10.1038/nature21360`.

[6] NASEM. *Pathways to Discovery in Astronomy and Astrophysics for the 2020s*. Washington, DC: The National Academies Press, 2021. ISBN: 978-0-309-46586-1. DOI: `10.17226/26141`. URL: `https://nap.nationalacademies.org/catalog/26141/pathways-to-discovery-in-astronomy-and-astrophysics-for-the-2020s`.

[7] Thomas Mikal-Evans. "Detecting the proposed CH4–CO2 biosignature pair with the James Webb Space Telescope: TRAPPIST-1e and the effect of cloud/haze". In: *Monthly Notices of the Royal Astronomical Society* 510.1 (2022), pp. 980–991.

[8] Nicholas F. Wogan and David C. Catling. "When is Chemical Disequilibrium in Earth-like Planetary Atmospheres a Biosignature versus an Anti-biosignature? Disequilibria from Dead to Living Worlds". In: 892.2, 127 (Apr. 2020), p. 127. DOI: `10.3847/1538-4357/ab7b81`. arXiv: `1911.06852 [astro-ph.EP]`.

[9] O. Lim et al. "Atmospheric Reconnaissance of TRAPPIST-1 b with JWST/NIRISS: Evidence for Strong Stellar Contamination in the Transmission Spectra". ApJL, in review.

[10] Benjamin V Rackham, Dániel Apai, and Mark S Giampapa. "The transit light source effect: false spectral features and incorrect densities for M-dwarf transiting planets". In: *The Astrophysical Journal* 853.2 (2018), p. 122.

[11] Joshua Krissansen-Totton. "Implications of Atmospheric Nondetections for Trappist-1 Inner Planets on Atmospheric Retention Prospects for Outer Planets". In: 951.2, L39 (July 2023), p. L39. DOI: `10.3847/2041-8213/acdc26`. arXiv: `2306.05397 [astro-ph.EP]`.

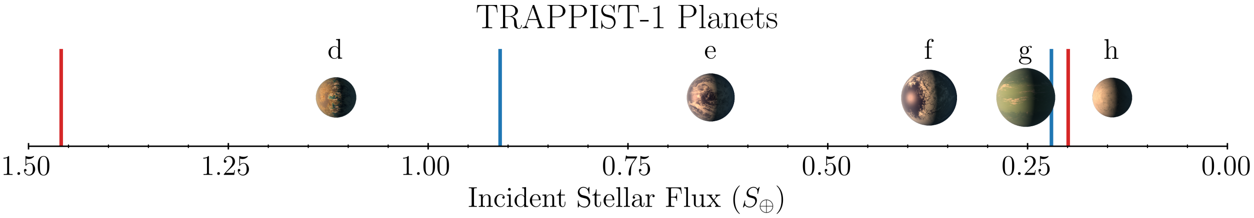

Figure 1: The TRAPPIST-1 system as a function of incident stellar flux relative to Earth's, with the optimistic (red) and conservative (blue) limits of the habitable zone. Measuring d and e's atmospheric composition to search for signs of ocean loss will provide the first observational test of the extent of the habitable zone.

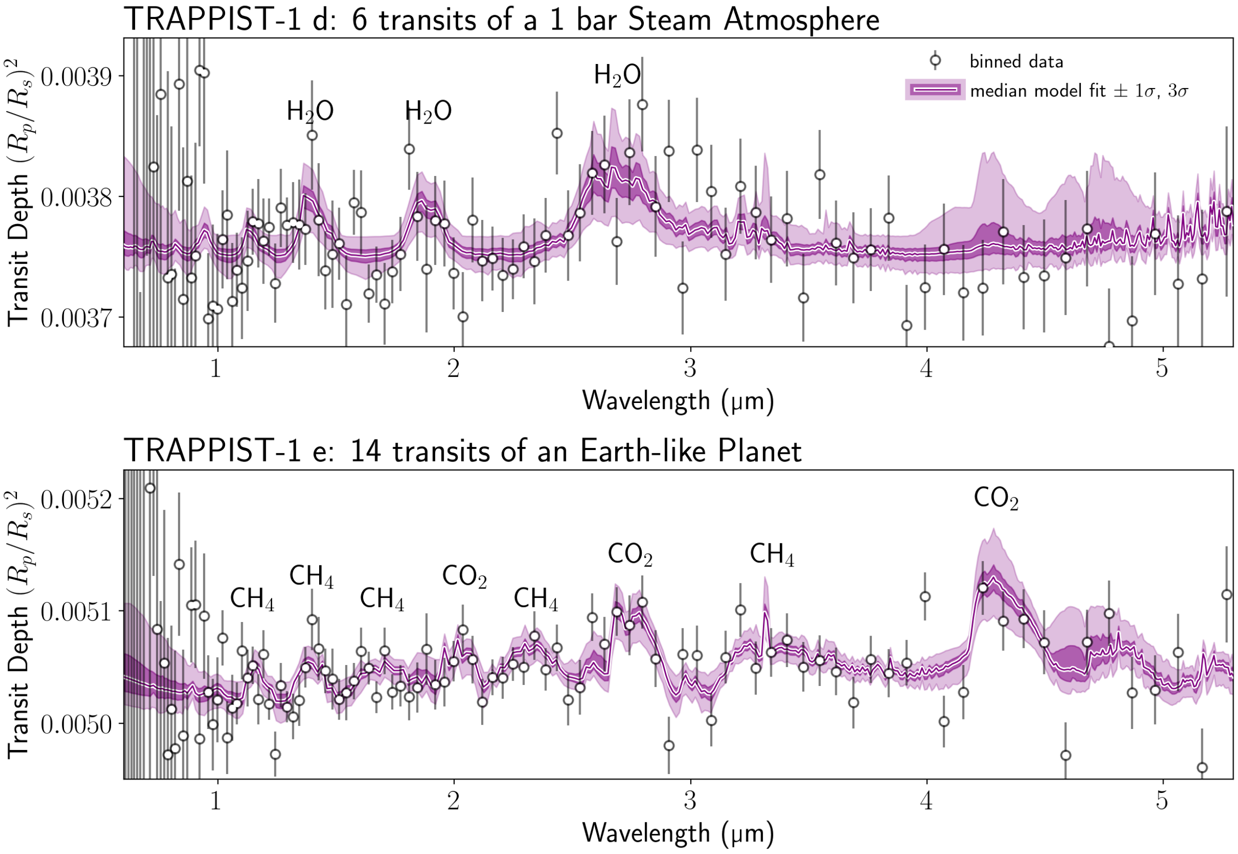

Figure 2: Simulated spectrum retrieval analyses for 6 transits of TRAPPIST-1 d (top) and 14 transits of TRAPPIST-1 e (bottom) showing sensitivity to key molecular absorption features. For a TRAPPIST-1 d steam atmosphere H_2O could be detected at 4.5σ. For a TRAPPIST-1 e modern Earth-like atmosphere these observations could provide a robust detection of the CO_2 (6.2σ) and CH_4 (5.4σ) biosignature pair. Image credit: J. Lustig-Yaeger