Constraining the habitability of rocky exoplanets in the Milky Way

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: The Kepler mission, ground-based surveys, and TESS have shown that rocky planets are relatively common in the Milky Way. Approximately 75% of all main-sequence stars in the Milky Way are M dwarfs, while only ∼20% are FGK [1]. Furthermore, M dwarfs are about twice as likely to host terrestrial planets [2], so Earth-sized rocky planets are nearly 10x more common around M dwarfs than FGK solar-type stars. Therefore, it is important to study the atmospheres of rocky planets around M dwarfs to understand habitability of the Galaxy. The seven transiting rocky planets of the TRAPPIST-1 system provide an excellent and unique laboratory for such observations. It is important to conduct multiple JWST secondary eclipse observations of the TRAPPIST-1 e habitable zone planet to measure its temperature and constrain its atmosphere. As little as 100 hours of JWST time (25 eclipses) could detect thermal emission from the planet if it has no atmosphere, and at least 400 hours (100 eclipses) would be needed for a more thorough characterization (all MIRI time-series imaging in the F1500W filter).

Anticipated Science Objectives: The rotations of planets in the habitable zones of M dwarfs are tidally locked to their orbits. These planets are also exposed to an extreme radiation environment due to an extended high-luminosity pre-main-sequence phase ($\sim$1 Gyr), frequent high-energy flaring, and likely associated coronal mass ejections from their stars. These phenomena may make it more difficult for M dwarf planets to retain atmospheres and support life [3, 4]. The nearby (13 pc) M8.5V star and 7 transiting rocky planets of the TRAPPIST-1 system [5] make it an excellent laboratory for studying the habitability of M-dwarf planets. Recent studies have detected the thermal emissions of planets b and c from JWST MIRI F1500W ($\lambda = 15\ \mu$m filter) secondary eclipse observations [6, 7]. Both planets have high brightness temperatures inconsistent with dense atmospheres that have CO_2 [8] or circulate heat around the planet. It is not totally surprising that they lack substantial atmospheres because they are interior to the star's habitable zone. However, recent models predict that the habitable zone planet TRAPPIST-1 e (T-1 e) has a 98% chance of retaining a substantial atmosphere [9].

All TRAPPIST-1 planets have been observed with transmission spectroscopy techniques using HST or JWST, and none of those programs have been able to constrain the presence or absence of a dense, high mean molecular weight atmosphere (as needed for life) for any of these planets. We advocate for JWST MIRI F1500W secondary eclipse observations of the habitable zone planet T-1 e to detect its thermal emission and constrain its atmospheric composition and opacity, the same technique successfully used on planets b and c [6, 7].

Urgency: Approximately 20 T-1 e secondary eclipses can be observed per year (2 x 60 day window / 6 day period), so observing 100 eclipses could take at least 5 years to complete. JWST will not last forever, so we need to start now!

Risk/Feasibility: Figure 1 shows that T-1 e would have a dayside brightness of 117 ppm relative to its star in the MIRI F1500W 13.5 – 16.7 μm bandpass if it has low albedo and does not have a thick atmosphere that recirculates heat to its night side. A 5 σ detection would require observing 25 eclipses, requiring about 100 hours of charged JWST time (σ = 114 ppm noise per observation). It would be more prudent to observe 100 secondary eclipses (400 hours) to extend sensitivity to detecting the planet if it has a dense atmosphere that recirculates its heat over its entire surface. A non-detection would indicate dense CO_2 in its atmosphere.

Timeliness: Mankind wants to know now how common life is in the universe.

Cannot be accomplished in the normal GO cycle: Hundreds of hours of JWST time over $\sim$ 5 years are beyond the scope of normal GO opportunities.

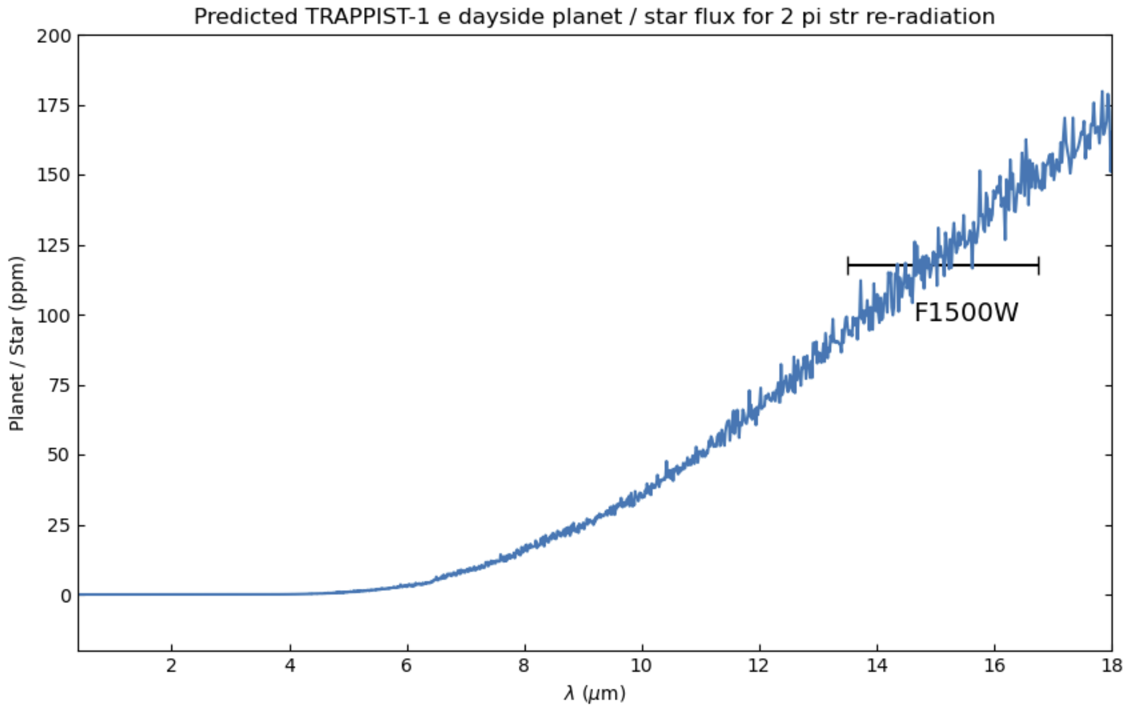

Figure 1: Estimated TRAPPIST-1 e planet / star flux for re-radiation of stellar flux over 2π str (maximum likely flux: no atmosphere / no redistribution). This models the planet as a zero-albedo blackbody with a dayside temperature of 297 K. Complete redistribution of the stellar flux over 4π str would produce an equilibrium temperature $T_{\mathrm{eq}} = 250$ K and would provide F_p/F_* = 62 ppm over the MIRI F1500W bandpass. F1500W is the most sensitive filter for this observation when the JWST PSF and thermal emission are considered.

References

[1] Todd J. Henry et al. “The Solar Neighborhood. XVII. Parallax Results from the CTIOPI 0.9 m Program: 20 New Members of the RECONS 10 Parsec Sample”. In: *Astron. J* 132.6 (Dec. 2006), pp. 2360–2371. DOI: 10.1086/508233. arXiv: astro-ph/0608230 [astro-ph].

[2] Courtney D. Dressing and David Charbonneau. “The Occurrence of Potentially Habitable Planets Orbiting M Dwarfs Estimated from the Full Kepler Dataset and an Empirical Measurement of the Detection Sensitivity”. In: *Astrophys. J.* 807.1, 45 (July 2015), p. 45. DOI: 10.1088/0004-637X/807/1/45. arXiv: 1501.01623 [astro-ph.EP].

[3] Jill C. Tarter et al. “A Reappraisal of The Habitability of Planets around M Dwarf Stars”. In: *Astrobiology* 7.1 (Mar. 2007), pp. 30–65. DOI: 10.1089/ast.2006.0124. arXiv: astro-ph/0609799 [astro-ph].

[4] Martin Turbet et al. “Modeling climate diversity, tidal dynamics and the fate of volatiles on TRAPPIST-1 planets”. In: *Astron. Astrophys.* 612, A86 (May 2018), A86.

[5] Michaël Gillon et al. "Seven temperate terrestrial planets around the nearby ultracool dwarf star TRAPPIST-1". In: *Nature* 542.7642 (Feb. 2017), pp. 456–460.

[6] Thomas P. Greene et al. "Thermal emission from the Earth-sized exoplanet TRAPPIST-1 b using JWST". In: *Nature* 618.7963 (June 2023), pp. 39–42. DOI: 10.1038/s41586-023-05951-7. arXiv: 2303.14849 [astro-ph.EP].

[7] Sebastian Zieba et al. "No thick carbon dioxide atmosphere on the rocky exoplanet TRAPPIST-1 c". In: *arXiv e-prints*, arXiv:2306.10150 (June 2023), arXiv:2306.10150. DOI: 10.48550/arXiv.2306.10150. arXiv: 2306.10150 [astro-ph.EP].

[8] Andrew P. Lincowski et al. "Evolved Climates and Observational Discriminants for the TRAPPIST-1 Planetary System". In: *Astrophys. J.* 867.1, 76 (Nov. 2018), p. 76.

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