Next step on the roadmap to the efficient and robust characterization of temperate terrestrial planet atmospheres with JWST

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 ($\sim$500 hours) Director's Discretionary exoplanet program to start implementation by JWST Cycle 3.

Summary: Ultra-cool dwarf stars are abundant, long-lived, and uniquely suited to enable the atmospheric study of transiting terrestrial companions with JWST. Amongst them, the most prominent is the M8.5V star TRAPPIST-1 and its seven planets, which have been favored targets of both HST & JWST programs. While JWST Cycle 1 observations have started to yield preliminary insights into the planets, they have also revealed that their atmospheric exploration requires a better understanding of their host star. Here, we introduce a roadmap to characterize the TRAPPIST-1 system—and others like it—in an efficient and robust manner. We notably recommend that—although more challenging to schedule—multi-transit windows be prioritized to constrain stellar activity (heterogeneities and flares) and gather up to 2$\times$ more transits per JWST hour spent. Therefore large-scale community-supported flagship programs should be favored for the exploration of such systems, rather than small individual projects that are difficult to coordinate. Finally, we recommend implementing urgently the next step on this roadmap—namely to assess the presence of an atmosphere around each of the TRAPPIST-1 planets—to ensure that the exploration of the system can be carried out in a timely manner (i.e., over JWST's lifetime).

Anticipated Science Objectives: One of the four main objectives of JWST relates to studying "the atmospheres of extrasolar planets, and perhaps even find the building blocks of life elsewhere in the universe." Such origins-of-life endeavors are only possible for terrestrial exoplanets orbiting ultra-cool dwarfs stars[1]. To date only one system has been found to be particularly amenable for in-depth studies, TRAPPIST-1[2]. While the presence of an atmosphere around the 2 inner planets of the system is possible using emission in different photometric bands, for the other 5 planets (d through h) transmission spectroscopy is required, but necessitates tackling the challenge of stellar contamination seen across a range of system in JWST Cycle 1 observations[3,4]. Leveraging the unique properties of the TRAPPIST-1 system (incl., frequent multi-transit windows[5]), we highlight the following proposed roadmap[6] to enable the exploration of a terrestrial planet system with JWST. **1.** MIRI/LRS emission observations of the inner planets to assess the presence of an atmosphere ($\sim$10 eclipses or 60 hr per planet and/or a joint phase curve, $\leq$70 hr). Step already in process[7,8] (PIDs 1177, 1279, 2304, and 3077). **2.** If one of the inner planets does have a "featureless" atmosphere such that its transmission spectrum records the transit light source (TLS) effect[9], the presence of an atmosphere around the other planets can be assessed via a first-order TLS correction supported by contemporaneous NIRSpec/PRISM transit of the featureless planet ($\leq$10 multi-transit windows per planets). **3.** If all inner planets appear to have an atmosphere, a full NIRISS/SOSS stellar rotation curve is needed to correct for TLS via empirical constraints on stellar models[10] and enable the search for the presence of an atmosphere around the other planets ($\sim$80 hr in addition to step 2). **4.** If an atmosphere is detected, its in-depth characterization may take upwards of $\sim$300 hr[1,6] and will require the empirical emission spectra of the stellar heterogeneities mentioned at step 3 to ensure a thorough correction of TLS.

Urgency + Timeliness: Each step spans multiple JWST Cycles. Swiftly transitioning to the next step is thus key to giving JWST a chance to succeed in its Origins of Life objective. Step 2 needs to be performed for each planet in the system. Indeed, an absence of atmosphere around the innermost planets has limited to no implications on the odds of outer planets retaining substantial atmospheres[11].

Risk/Feasibility: A null result (no atmosphere in the system) is possible, and would still provide valuable insights into their interior compositions given their masses (incl. tight constraints on volatile reservoirs). In addition, a series of quasi-contemporaneous transits of atmosphereless planets with different impact parameters would provide exquisite constraints on TRAPPIST-1's heterogeneities, to inform the exploration of other systems and benchmark the next-gen of stellar models. Finally, the ultra-precise transit timings will help confirm an 8^{th} planet[12]. **Cannot be accomplished in the normal GO cycle**: The observational strategy is unique to such a system both in terms of time investment and scheduling constraints, which requires a pioneering program beyond the scope of a typical GO program. For the next step, up to 10 specific windows of up to 12 hours are required over the next 18 months.

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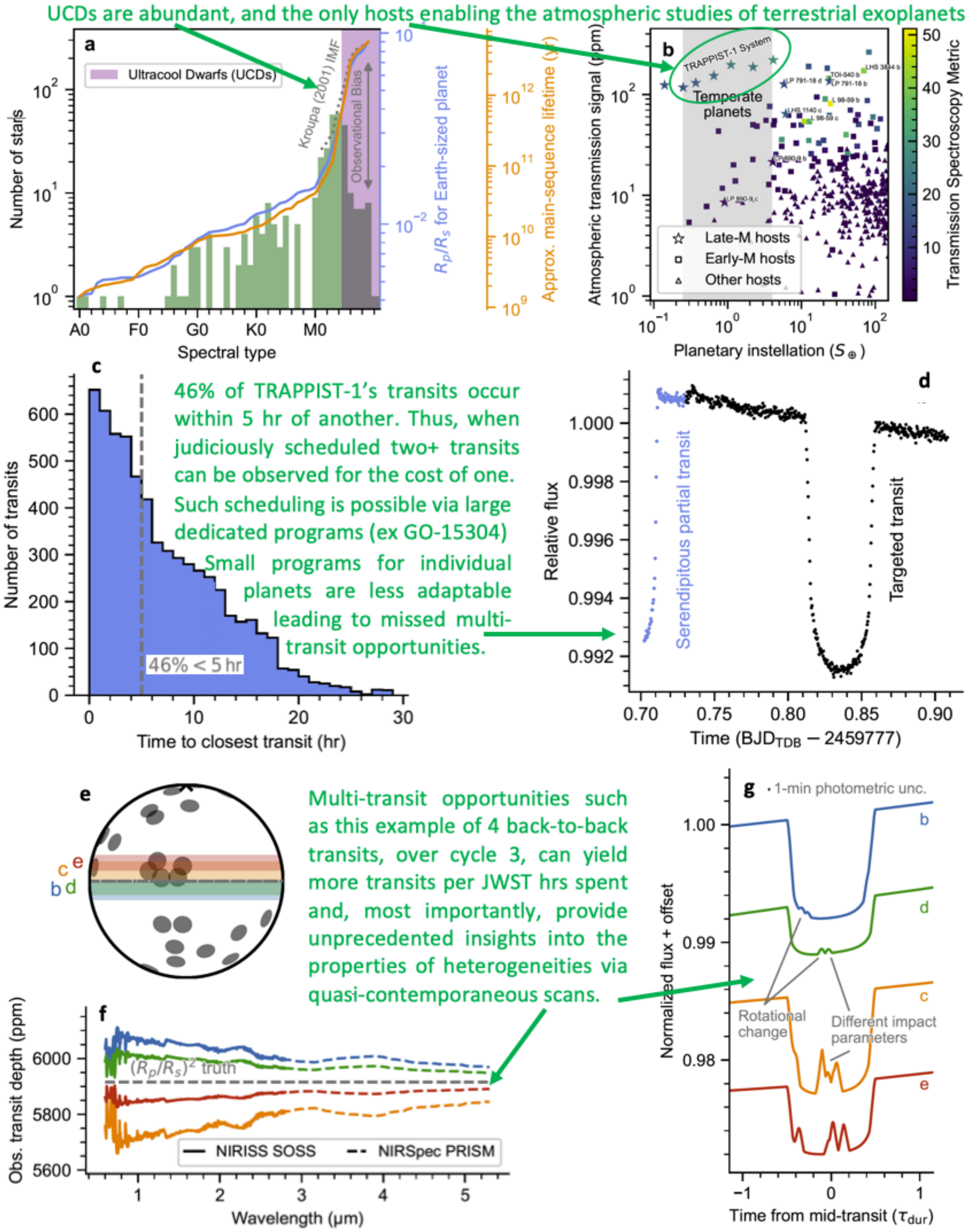

Figure 1: **a.** Histogram of spectral types of all stars within 10 pc observed by Gaia together with the main-sequence lifetime (orange) and expected transit depth for a terrestrial planet for each type (blue). **b.** Most promising terrestrial planets for atmospheric characterization. Planets transiting late-M, early-M, and other hosts are shown as stars, squares, and triangles, respectively. Colors illustrate the transmission spectroscopy metric. **c.** Histogram of time-to-closest-transit for each TRAPPIST-1 transit event between 2015–2025. **d.** Serendipitous partial transit of TRAPPIST-1 b during the first GO-2589 observation of TRAPPIST-1 g. **e.** Schematic representation of different transits during a multi-transit event of planets b, c, d, and e in Cycle 3. **f.** Contaminated transmission spectra for the same transit train of planets b–e (coloured lines). A nominal planet radius of 1 $R_\oplus$ (dashed gray line) is used for each planet to ease comparisons of the TLS effect for each planet. **g.** Close-up view of the transit profiles for the four-planet transit train, highlighting repeated occultations of the same active regions by planets b and d as well as c and e, whose transit chords overlap in this simulation.