Know Thy Star, Know Thy Planet: In-Depth Stellar Activity Characterization of Trappist-1

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: There are now ample evidence from Cycle 1 JWST observations that stellar activity in the form of flares, the transit light source (TLS)[1] effect associated with unocculted spots/faculae and spot crossing events constitute a significant source of contamination of transmission spectra of exoplanets, from hot Jupiters[2] to small M dwarfs like Trappist-1[3,4]. For the latter, flares are very frequent (one every ∼8 hours)[5], the TLS was observed to be strong (several hundreds of ppm) and variable in Trappist-1b[3], yet intriguingly modest (<50 ppm) in Trappist-1g[4]. Correcting transmission spectra from stellar activity is absolutely crucial, and possible[6], in order to reach the ∼50 ppm sensitivity required to detect thin secondary atmospheres in Trappist-1 planets[7] and many other small planets orbiting low-mass M dwarfs for which stellar activity is commonly observed. We propose to observe Trappist-1 with NIRISS/SOSS continuously over a full rotation period (80 hrs) to extract, for the first time, the emission spectra of different surface heterogeneities, constrain their spatial and temporal distribution/evolution and determine the occurrence rate of flares and quantify their impact on transmission spectra. This unique data set will enhance the scientific return of all past, present, and future transmission spectroscopic observations of numerous planetary systems by providing the empirical inputs directly needed to correct for stellar contamination. This program will open a new era of *precision* transmission spectroscopy in which stellar activity is properly and accurately corrected for to enable detailed atmospheric characterization of exoplanets, especially small ones.

Anticipated Science Objectives:

Assessing the habitability of rocky planets orbiting low-mass stars is a top priority for the JWST mission. Focused studies, such as eclipse and transmission spectroscopy on key targets like the Trappist-1 system, are essential. Initial Cycle 1 observations revealed that stellar activity can cause transit depth variations exceeding several of hundred of ppm in Trapppist-1b[3]. This calls for an in-depth characterization of Trappist-1's stellar activity through a continuous spectroscopic monitoring over one full rotation (3.3 days; 80 hrs) using NIRISS/SOSS as well an effective multi-transit approach[8] for the next phase of in-depth atmospheric characterization of all Trappist-1 planets using NIRSpec/PRISM[9].

Urgency: While several model-based[3] and data-driven methods[6] have already been developed to correct transmission spectra for the TLS effect, one has yet to learn in detail how to properly correct transmission spectra for stellar activity. It is crucial to subject these methods to rigorous benchmarking and testing against a comprehensive stellar activity data set, as proposed here. This step is essential to optimize the scientific outcomes of all transmission spectroscopy programs.

Risk/Feasibility: This program clearly falls under the rare category of low risk and high reward, as it has the potential to be truly transformative for transmission spectroscopy. Regardless of the program's low risk in achieving precise corrections for stellar activity, it offers additional scientific benefits, such as unique insights into flare physics[5], advancements in stellar atmosphere modeling, and the assurance of nine free transit events (see Figure 1). This situation is akin to the precision radial velocity field from about a decade ago, which had to develop methods to extract Keplerian signals significantly smaller than those generated by stellar activity. Thanks to various empirically-derived activity indicators and innovative analysis techniques developed from extensive data sets, one now routinely detects Keplerian signals smaller than those produced by stellar activity near the photon-noise limit (e.g. Proxima d[10]).

Timeliness: Given the ample evidence of stellar activity as a potential obstacle to characterizing small exoplanet atmospheres and the availability of corrective promising model-based[3] and data-driven solutions[6], it's time to undertake a comprehensive stellar characterization of the Trappist-1 star.

Cannot be accomplished in the normal GO cycle: This program fits within the large GO program criteria and will be promptly submitted. However, its rejection, coupled with the annual proposal submission process, may impede the community's full use of exoplanet transmission spectroscopy data for several years.

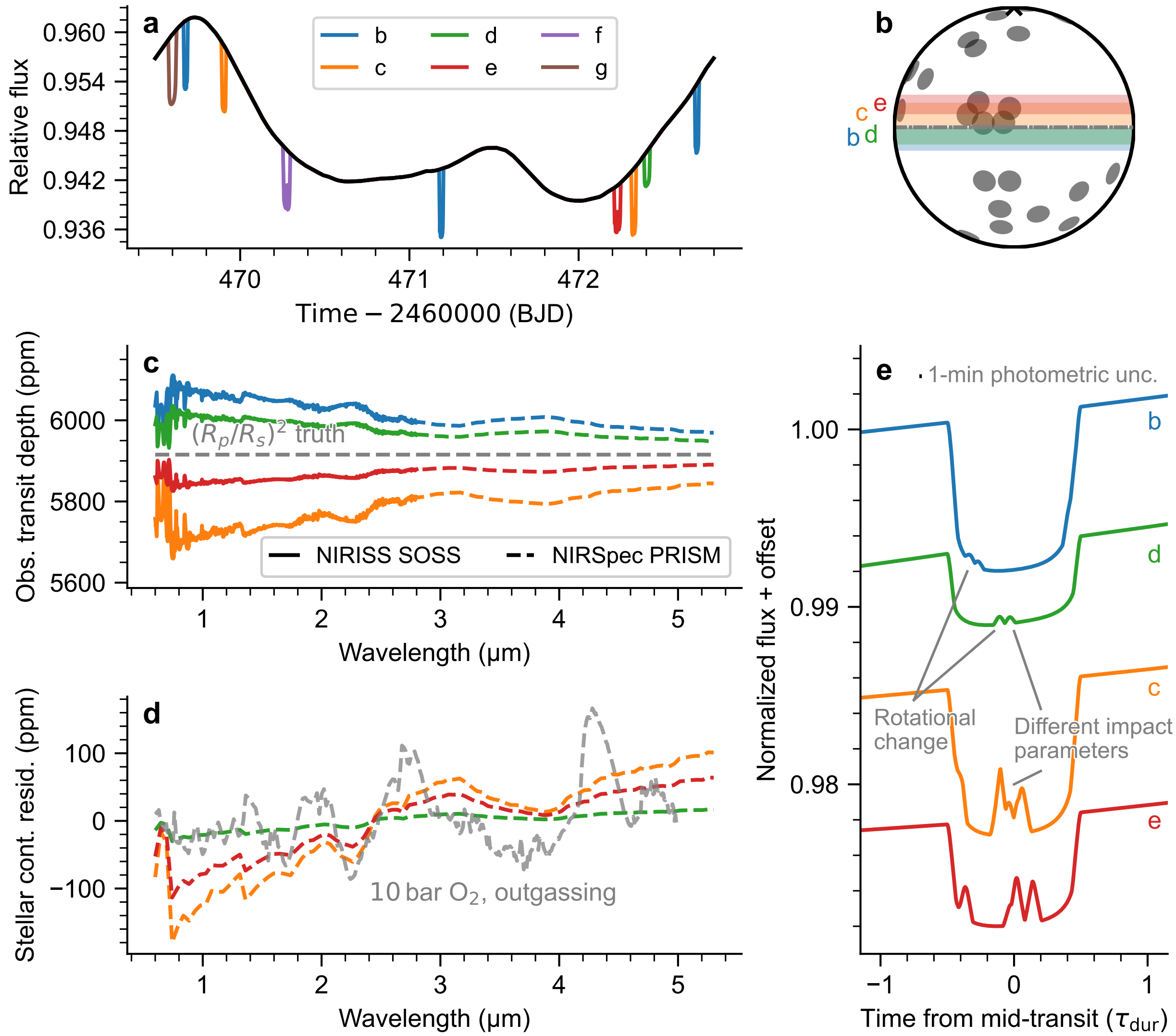

Figure 1: **Constraining the surface heterogeneities of a host star.** **a.** A simulated 3.3-d full rotation curve of TRAPPIST-1 (black line) featuring nine transits of six planets (coloured lines). **b.** A snapshot of the spot distribution at the last rotational phase of the simulation shown in panel a, with the transit chords of planets b, c, d, and e. **c.** 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. **d.** The residual stellar contamination signals for the simulated transits of planets c–e (coloured lines), after correcting for the TLS effect using the in-transit signal from planet b. A median-subtracted model of an atmosphere is shown for comparison (gray dashed line). **e.** 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.

References

[1] Rackham, B., Apai, D. & Giampapa, M.S. Triaud, A., The Transit Light Source Effect: False Spectral Features and Incorrect Densities for M-dwarf Transiting Planets, ApJ, 853, 122 (2018).
[2] Fournier-Tondreau, M et al., Near-Infrared Transmission Spectroscopy of HAT-P-18 b with NIRISS: Disentangling Planetary and Stellar Features in the Era of JWST, MNRAS, under review.
3 Lim, O. et al., Atmospheric Reconnaissance of TRAPPIST-1 b with JWST/NIRISS: Evidence for Strong Stellar Contamination in the Transmission Spectra. ApJL, accepted.
4 Benneke, B. et al., No substantial secondary atmosphere or high-altitude clouds on the habitable-zone exo-Earth TRAPPIST-1g, Nature, in review.
[5]Howard., W. et al., Characterizing the Near-infrared Spectra of Flares from TRAPPIST-1 During JWST Transit Spectroscopy Observations, ApJ, under review.
[6]Berardo, D., de Wit, J. & Rackham, B. V. Empirically Constraining the Spectra of a Stars Heterogeneities From Its Rotation Lightcurve. ApJL, in review. arXiv:2307.04785.
[7] Lustig-Yaeger, J., Meadows, V. & Lincowski, P., The Detectability and Characterization of the TRAPPIST-1 Exoplanet Atmospheres with JWST, ApJ, 158, 27 .
[8]de Wit, J., Wakeford, H. R., Lewis, N. et al. Atmospheric reconnaissance of the habitable-zone Earth-sized planets orbiting TRAPPIST-1. Nature Astronomy 2, 214–219 (2018).
[9]TRAPPIST-1 JWST Community Initiative, de Wit, J., Doyon, R. et al. A roadmap to the efficient and robust characterization of temperate terrestrial planet atmospheres with JWST. Nature Astronomy, in review.
[10] Faria, J.P. et al., A candidate short-period sub-Earth orbiting Proxima Centauri, A&A, 658, 115.