Cool Planets Legacy Survey

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: We propose that JWST undertake a Cool Planets Legacy Survey, a thorough study of some of the rarest transiting planets that would be sensitive to phenomena yet to be detected beyond our solar system. When targeting a handful of carefully selected systems, NIRSpec PRISM observations are capable of revealing Ganymede-sized moons, planetary rings, and evidence of planetary oblateness. All three of these attributes are common within our own solar system but were nearly undetectable in others prior to the deployment of JWST. Consequently, only now can we place limits on their occurrence rates through both detections and meaningfully sensitive non-detections. These constraints grow stronger as our sample size increases; however, since catching moons requires inflating the baseline of each individual transit observation beyond usual practices, it would be difficult to accumulate a large enough sample of observations through the usual GO process. A large Legacy Survey is a well-suited solution to this issue, and could further contextualize our solar system and its so-far uniquely rich complexity.

Anticipated Science Objectives: We now know of thousands of planetary systems, yet our own continues to stand out among them. Around our Sun, every major planet beyond 1 AU has moons; some are notably oblate, and some have rings. None of these features have been detected elsewhere, but until the successful deployment of JWST, such detections were prohibited by insufficiently precise instrumentation. A Cool Planets Legacy Survey could place the first meaningful limits on the occurrence rates of these three attributes. Additionally, though not the primary objective of a campaign targeting cold planets, we expect to be able to characterize the atmospheric chemistry of a subsample of the targets as well (e.g. TOI-4600c).

Urgency: The longest period, cool planets discovered by Kepler and TESS are a rare and precious sample, both in the sense of defying the strong detection bias of transit surveys but also very infrequently transiting. Indeed, with their long periods and JWST's finite lifetime, each missed transit is a lost opportunity. Discovering moons is particularly urgent for planning of future imaging missions like the Habitable Worlds Observatory, since moon spectra intermix with those of the planet creating an apparent chemical disequilibrium signal i.e. a biosignature false-positive [1].

Risk/Feasibility: In a small handful of systems (Table 1), JWST is sensitive to moons as small as Ganymede. However, since this survey would place the first limits on the occurrence of extrasolar moons/rings/oblateness beyond an AU, we do not know at present how common these features are, so we cannot predict the number of detections. Regardless, a guaranteed science product is the occurrence rate of these phenomena. It would be perhaps an even more astonishing result if the Solar System is unusual in harboring large moons.

Timeliness: As discussed, each Cool Planet's transits are relatively rare: Kepler-167e, for example, is a well-characterized Jupiter analog that only transits every $\sim$3 years [2, 3]. Should a Cool Planets survey reveal anything that requires follow-up, there will be limited opportunities for it during JWST's lifetime. Therefore, we are motivated to search these systems as early as possible.

Cannot be accomplished in the normal GO cycle: To place meaningful constraints on the occurrence rates of these three never-before-detected exoplanet attributes, we must look for them in a statistically meaningful number of systems. However, since each individual target requires $\sim$50 hours of observations, a large enough dataset cannot be accumulated through a normal GO cycle.

Planet	Type	Equilibrium Temp (K)	Period (days)	1-transit SNR of Isolated Moon	Baseline Required (hours)	# Transits
Kepler-167 e	Giant	134	1071	7.5	57.78	3
TOI-4600 c	Giant	191	484	6.0	39.45	3
Kepler-539 b	Giant	388	126	3.9	24.11	2
Kepler-186 f	Terrestrial	177	130	9.6	25.53	2
Kepler-62 f	Terrestrial	208	267	6.3	32.80	2
Kepler-1229 b	Terrestrial	212	89	4.7	19.43	2
Total Allocation:						495.43

Table 1: Potential targets for a Cool Planets Legacy Survey. The baselines are chosen to guarantee that a moon at Ganymede's separation would be captured even if it maximally led or lagged behind the planet. The SNR of an isolated moon is calculated by first computing the precision of a depth measurement assuming a box transit model, which itself is based on noise estimates computed using the most up-to-date version of the official online JWST ETC. This precision is then compared to the depth of a Ganymede-radius moon in that particular system. These values meant to illustrate that JWST is sensitive to the dips of a Ganymede-sized objects within these system, although in reality, the data would be fit with a more complex photodynamical model [4, 5].

References

[1] Hanno Rein, Yuka Fujii, and David S. Spiegel. "Some inconvenient truths about biosignatures involving two chemical species on Earth-like exoplanets". In: *Proceedings of the National Academy of Sciences* 111.19 (May 2014). Publisher: Proceedings of the National Academy of Sciences, pp. 6871–6875. DOI: `10.1073/pnas.1401816111`.

[2] D. M. Kipping et al. "A Transiting Jupiter Analog". en. In: *The Astrophysical Journal* 820.2 (Mar. 2016). Publisher: The American Astronomical Society, p. 112. ISSN: 0004-637X. DOI: `10.3847/0004-637X/820/2/112`.

[3] Yayaati Chachan et al. "Kepler-167e as a Probe of the Formation Histories of Cold Giants with Inner Super-Earths". en. In: *The Astrophysical Journal* 926.1 (Feb. 2022). Publisher: The American Astronomical Society, p. 62. ISSN: 0004-637X. DOI: `10.3847/1538-4357/ac3ed6`.

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[5] Tyler A. Gordon and Eric Agol. "Analytic Light Curve for Mutual Transits of Two Bodies Across a Limb-darkened Star". en. In: *The Astronomical Journal* 164.3 (Aug. 2022). Publisher: The American Astronomical Society, p. 111. ISSN: 1538-3881. DOI: `10.3847/1538-3881/ac82b1`.