The Search for Rocky Exoplanet Atmospheres

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:

After two decades of operation, one of JWST's lasting legacies will be the first, detailed study of terrestrial exoplanets. Using both transit and eclipse observations, JWST will reveal the host star characteristics that enable these rocky worlds to host substantial atmospheres. JWST will ultimately unveil the diversity of atmospheric compositions and thermal structures, many of which will be actively sculpted by geochemistry, photochemistry, magnetic interactions, and more. The best pathway to achieving this outcome is a large-scale Director's Discretionary program dedicated to observing rocky, M-dwarf planets.

We advocate for the study of ∼15 high-priority targets (see Table 1) in both transmission (NIRISS/SOSS + NIRSpec/G395) and emission (MIRI). In place of simply picking the highest SNR planets, the target list should span a range of planet and host-star properties that adequately explore the multi-dimensional nature of the cosmic shoreline [1]. A detailed understanding of the host star's impact also requires contemporaneous X-ray to NUV observations using XMM-Newton and HST. The irradiation a planet receives at these wavelengths is expected to drive atmospheric loss [e.g., 2, 3]. To date, Cycle 1 programs have yielded tantalizing, yet inconclusive, evidence for secondary atmospheres [4, 5]. Higher precision data and broader wavelength coverage are needed to tease out these weak signals and resolve current degeneracies.

Anticipated Science Objectives: *What planetary and host-star characteristics enable rocky, M-dwarf planets to have substantial atmospheres?* Answering this question requires: **(1)** A large selection of targets (Table 1) spanning a range of planet temperatures, radii, and masses and stellar temperatures, ages/rotation rates, and activity levels; **(2)** Planet spectra with broad wavelength coverage (1 – 5 μm in transmission, 5 – 12 μm in emission); and **(3)** The full stellar SED (X-ray from XMM-Newton, XUV – optical from HST, and NIR – MIR from JWST).

Observations of multi-planet systems are valuable testbeds because they directly explore the effects of planetary properties for targets with similar formation and evolution histories. An emphasis should be placed on older, slow-rotating M dwarfs with lower activity levels, spanning a range of temperatures (i.e., not only TRAPPIST-1). The broad wavelength coverage in transmission is required to disentangle atmospheric water features from the transit light source effect [6].

Urgency: One of JWST's lasting legacies could be taking the next steps towards answering the question, *Are we alone?* Doing so will require years, possibly decades, of observations to build up sufficient knowledge. Starting the investigation in Cycle 3 will give JWST the best chance to answer the science objectives.

Risk/Feasibility: *This concept is high risk, high reward.* There is a risk that only a small fraction of rocky planets have atmospheres; however, understanding where these atmospheres "turn on" will inform future NASA-led missions by revealing the effects of XUV irradiation on planetary atmospheres. *This concept is feasible.* Cycle 1 programs have shown that JWST instrument are near-photon limited and can achieve the required precision to detect molecular absorption features in transmission and constrain the brightness temperature in emission.

Timeliness: For the first time in human history, we have the technological means to search for habitability indicators in an exoplanet atmosphere. The Astro2020 decadal survey has set the search for biosignatures as one of its top priorities [7].

Cannot be accomplished in the normal GO cycle: Observing the top 15 targets from Table 1 requires $\sim$500 hours of telescope time, which is well outside the scope of a normal GO cycle. Based on successful observing strategies [e.g., 4, 8, 9], this calculation assumes the listed number of transits for each of NIRISS/SOSS and NIRSpec/G395 and the listed number of eclipses for each of MIRI/LRS and F1500W. We did not apply any JWST overheads, nor did we account for existing observations from previous cycles. This target list is purely demonstrative; the final list should more uniformly explore the cosmic shoreline parameter space.

Table 1: Target list for a concept program utilizing both transit and eclipse observations.

	Rp (Earth)	T_{eq} (K)	Period (Days)	K_{mag}	T_{eff} (K)	TSM	ADS (σ)	# Tr.	ESM (15 μm)	ADS (σ)	# Ecl.
TOI 136.01	1.54	791	0.46	9.1	3004	574.3	4.32	2	64.5	17.95	2
L 98-59 b	0.88	619	2.25	7.1	3412	69.0	4.29	2	5.7	2.66	4
GJ 486 b	1.32	703	1.47	6.4	3340	65.1	4.23	2	32.0	13.66	2
TOI 486.01	0.66	750	1.74	7.0	3470	43.5	4.06	2	4.6	2.52	4
TOI 6008.01	1.21	710	0.86	9.5	3098	45.8	3.17	2	17.3	7.21	2
LHS 1140 c	1.10	399	3.78	8.8	2988	40.1	3.14	2	4.8	3.82	2
TOI 2267.03	0.88	504	2.29	9.5	3022	43.0	2.98	2	4.6	2.61	4
GJ 357 b	1.21	527	3.93	6.5	3505	33.6	2.82	3	6.4	4.39	2
LTT 1445 A b	1.32	429	5.36	6.5	3340	37.2	2.82	3	6.5	5.30	2
TOI 1450.01	1.10	722	2.04	7.6	3407	38.2	2.64	3	10.8	4.51	2
TOI 2267.01	1.21	438	3.50	9.5	3022	37.4	2.59	3	5.3	3.54	2
TOI 910.01	0.88	604	2.03	7.7	3312	41.3	2.39	3	5.8	2.30	5
LTT 1445 A c	1.10	513	3.12	6.5	3340	48.0	2.39	3	8.5	3.32	3
TRAPPIST-1 d	0.77	287	4.05	10.3	2566	37.9	2.36	3	0.5	0.60	70
TRAPPIST-1 b	1.10	399	1.51	10.3	2566	43.4	2.35	3	5.0	2.88	4
L 98-59 c	1.32	515	3.69	7.1	3412	32.1	2.34	3	7.3	4.33	2
TRAPPIST-1 c	1.10	341	2.42	10.3	2566	38.9	2.18	4	2.5	2.00	7
TOI-244 b	1.54	459	7.40	8.0	3433	168.7	2.17	4	4.1	3.45	3
TOI 6245.01	0.88	459	3.22	9.4	3106	30.1	2.08	4	2.5	1.56	11
L 98-59 d	1.54	407	7.45	7.1	3412	279.6	2.05	4	4.2	2.20	6
LP 791-18 d	0.99	429	2.75	10.6	2960	29.5	2.05	4	2.5	1.65	10
TRAPPIST-1 e	0.88	251	6.10	10.3	2566	27.7	1.95	5	0.3	0.52	95
TOI-1693 b	1.43	761	1.77	8.3	3499	25.4	1.94	5	11.2	5.29	2
TRAPPIST-1 h	0.77	172	18.77	10.3	2566	26.9	1.92	5	0.0	0.08	4131
GJ 3473 b	1.21	768	1.20	8.8	3347	26.9	1.91	5	10.8	4.21	2
LP 791-18 b	1.21	612	0.95	10.6	2960	35.7	1.88	5	12.3	4.47	2
LHS 1140 b	1.65	213	24.74	8.8	2988	132.1	1.88	5	0.3	1.33	15
GJ 1132 b	1.10	584	1.63	8.3	3270	28.0	1.78	6	7.3	3.21	3
TOI 1468.02	1.43	682	1.88	8.5	3382	25.7	1.78	6	11.4	4.95	2
TOI 1276.01	1.32	360	6.26	9.9	3145	16.2	1.73	6	1.4	1.95	7
TRAPPIST-1 f	0.99	218	9.21	10.3	2566	22.8	1.73	6	0.1	0.38	171
TOI-540 b	0.88	611	1.24	8.9	3216	34.0	1.69	6	5.0	1.64	10
TRAPPIST-1 g	1.10	198	12.35	10.3	2566	22.4	1.69	6	0.1	0.31	254

[1] TSM/ESM = Transmission/Emission Spectroscopy Metric [10].
[2] ADS = Atmospheric Detection Significance (per transit/eclipse). For transits, we assume an Earth-like atmosphere ($\mu = 28.964$). For eclipses, $ADS = (T_{day} - T_{eq,f=1})/T_{precisionPerEclipse}$ at 15 μm.
[3] # Tr/Ecl = Number of NIRSpec transits / MIRI eclipses (minimum two) to detect an atmosphere at 4σ/5σ confidence. Resolving the TLS effect would require additional transits using NIRISS/SOSS. We recommend against observing a target in a given mode if it requires $\gtrsim$6 visits.
[4] Targets above the red line fit into a ~500-hour program (skipping TRAPPIST-1d in emission).
[5] Assuming a Venus-like atmosphere ($\mu = 43.45$), targets above the blue line fit into a ~500-hour program. Here, the number of required transits is $1.5\times$ the listed values.

References

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