A Best-in-Class Statistical Survey of 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: A senior member of the exoplanet field once said "exoplanets are like galaxies." He meant that we know of hundreds of exoplanets ideally suited for ensemble characterization, which is a more powerful route to advancing our understanding of planets than object-by-object studies. The excellent performance of JWST and its anticipated lifetime of well over a decade puts statistical characterization of exoplanet atmospheres firmly within reach. This white paper outlines a straw-person[1] proposal for a systematic "Best-in-Class" survey of exoplanet atmospheres. We outline an observational approach to obtain panchromatic transmission spectra spanning a broad planetary parameter space (defined by planet size and equilibrium temperature) for the highest S/N targets that are currently known in order to address population-level questions about planet formation, evolution, and atmospheric properties. Such a survey would have far-reaching impact and would aid in defining the scientific agenda for the exoplanet field for years to come.

[1]What we describe in this document is only one possible realization of an exoplanet atmospheres statistical survey. Iterations on this survey approach could involve targeting planets in thermal emission rather than transmission, observing multiple transits per target to achieve a minimum S/N, employing a different target selection function, etc.

Survey Design: The Best-in-Class Survey would obtain broad wavelength (0.6–5 μm) transmission spectroscopy measurements for a representative sample of the highest S/N transiting planet targets. We advocate for transmission spectroscopy and coverage from both the NIRISS/SOSS and NIRSpec/G395H observing modes because this approach will yield simultaneous constraints on both atmospheric composition (i.e. metallicity and C/O) and aerosol properties for planets ranging from ultra-hot Jupiters to temperate sub-Neptunes. Rocky planets are excluded from this survey because they have unique science goals and require more intensive efforts to characterize. A 500-hr DDT program would enable approximately 50 individual transits to be observed, assuming $\sim$10 hrs/transit. We divide the observationally accessible parameter space into bins of equilibrium temperature and planet radius (Fig. 1), and we find that this approach also provides good coverage of planet masses (Fig. 2). The goal is to evenly sample the defined parameter grid-space, to the extent possible. DDT time should first go to filling out wavelength coverage for targets that have previously been observed by JWST with a single instrument mode, with new targets being incorporated thereafter.

Science Goals: The scientific drivers behind the Best-in-Class survey are to understand how planets form and evolve and to constrain the physical and chemical processes that sculpt planetary environments. Specifically, this survey allows for recovery of population-level trends in atmospheric composition and aerosol properties across the observed parameter space (e.g. Fig. 2). The Best-in-Class survey would additionally provide exciting discovery space opportunities by obtaining high-precision spectra covering previously unobserved wavelengths and in corners of parameter space that have been overlooked by GO programs.

An Optimal Use of DDT: The Best-in-Class survey leverages existing GO/GTO data to become more than the sum of their parts by filling in missed wavelengths and regions of planetary parameter space to create a uniform sample. The goals of this survey will not be achieved via the GO program alone because the TAC is not assigned to think holistically, as evidenced from uneven coverage of wavelengths and planet types in Cycles 1 & 2 (Fig. 1). By observing the highest S/N atmospheric characterization targets, the Best-in-Class survey is assured to deliver high-quality spectra and high-impact science. This will not be a program that produces null results and ambiguous interpretations. Even if certain planets return featureless transmission spectra (e.g. cool sub-Neptunes), these will be high S/N measurements that will provide critical population-level information on aerosol processes that cannot be extracted on an individual-planet basis.

Cycle 1+2 full 0.6-5 μm coverage | Cycle 1+2 prism coverage | Cycle 1+2 partial wavelength coverage | **Best-in-Class DDT target**

	100-350 K	350-800 K	800-1250 K	1250-1750 K	1750-2250 K	2250-3000 K
10-25 R_Earth	[15] Kepler-86 b (prism)	[959] WASP-107 b (SOSS+G395)	[450] WASP-39 b (SOSS+G395)	[851] WASP-127 b (SOSS+G395)	[153] HAT-P-65 b (prism)	[317] WASP-121 b (SOSS+G395)
		[179] TOI-1130 c (SOSS+G395)	[282] HAT-P-12 b (SOSS+G395)	[423] WASP-17 b (SOSS+G395)	**[262] KELT-7b (G395)**	**[301] WASP-189 b (SOSS)**
		[204] TOI 3757 b (prism)	**[743] WASP-69 b (G395)**	[130] Kepler-12 b (prism)	**[484] WASP-76 b**	**[220] WASP-178 b (G395)**
		[146] TOI-3235 b (prism)	**[291] WASP-80 b (G395 equiv.)**	[42] NGTS-10 b (prism)	**[391] HAT-P-32 b**	**[463] WASP-33 b**
		[138] HATS-6 b (prism)	**[247] HAT-P-18 b (SOSS)**	**[578] WASP-94 A b (G395)**	**[317] WASP-74 b**	**[177] WASP-12 b**
4-10 R_Earth	**[24] Kepler-30 d**	[180] HATS-72 b (SOSS+G395)	[273] HAT-P-26 b (SOSS+G395)	[255] WASP-166 b (SOSS+G395)	[185] LTT 9779 b (SOSS+G395)	
		[137] TOI-3984.01 (prism)	**[229] HD 332231 b**	**[203] HD 149026 b**	**[33] K2-39 b**	
		[52] HATS-75 b (prism)	**[204] WASP-139 b**	**[111] WASP-182 b**		
		[302] GJ 3470 b (G395 equiv.)	**[187] HAT-P-11 b**	**[107] TOI-954 b**		
		[463] GJ 436 b	**[163] TOI-181 b**	**[99] HATS-38 b**		
1.5-4 R_Earth	[100] TOI-1231 b (SOSS+G395)	[232] GJ 3090 b (SOSS_G395)	[88] TOI-421 b (SOSS+G395)	**[89] HD 86226 c**	**[26] TOI-2196 b**	
	[66] TOI-1468 c (SOSS+G395)	[111] LTT 3780 c (SOSS+G395)	[85] GJ 9827 b (SOSS+G395)	**[68] TOI-824 b**	**[21] TOI-849 b**	
	[31] K2-18 b (SOSS+G395)	[87] L 231-32 d (SOSS+G395)	[82] TOI-1130 b (SOSS+G395)	**[50] TOI-4010 b**		
		[138] LP 791-18 c (prism)	**[59] TOI-125 c (G395)**	**[40] TOI-132 b**		
		[115] TOI-178 g (G395)	**[50] TOI-125 b (G395)**	**[23] NGTS-4 b**		

Figure 1: An *example* target list. Bold pink text indicates the targets for the DDT program. Colored highlighting indicates the wavelength coverage for programs in Cycles 1 & 2, as indicated. Targets in yellow require additional observations to complete the 0.6-5 μm wavelength coverage. Planets observed with the PRISM mode formally meet the wavelength coverage requirements of the survey, but may suffer from saturation and/or uneven S/N. New targets for the DDT program are selected via their TSM, indicated in brackets. The total sample consists of 68 planets (including 4 not shown) and fills in regions of parameter space that are unpopulated by current JWST programs.

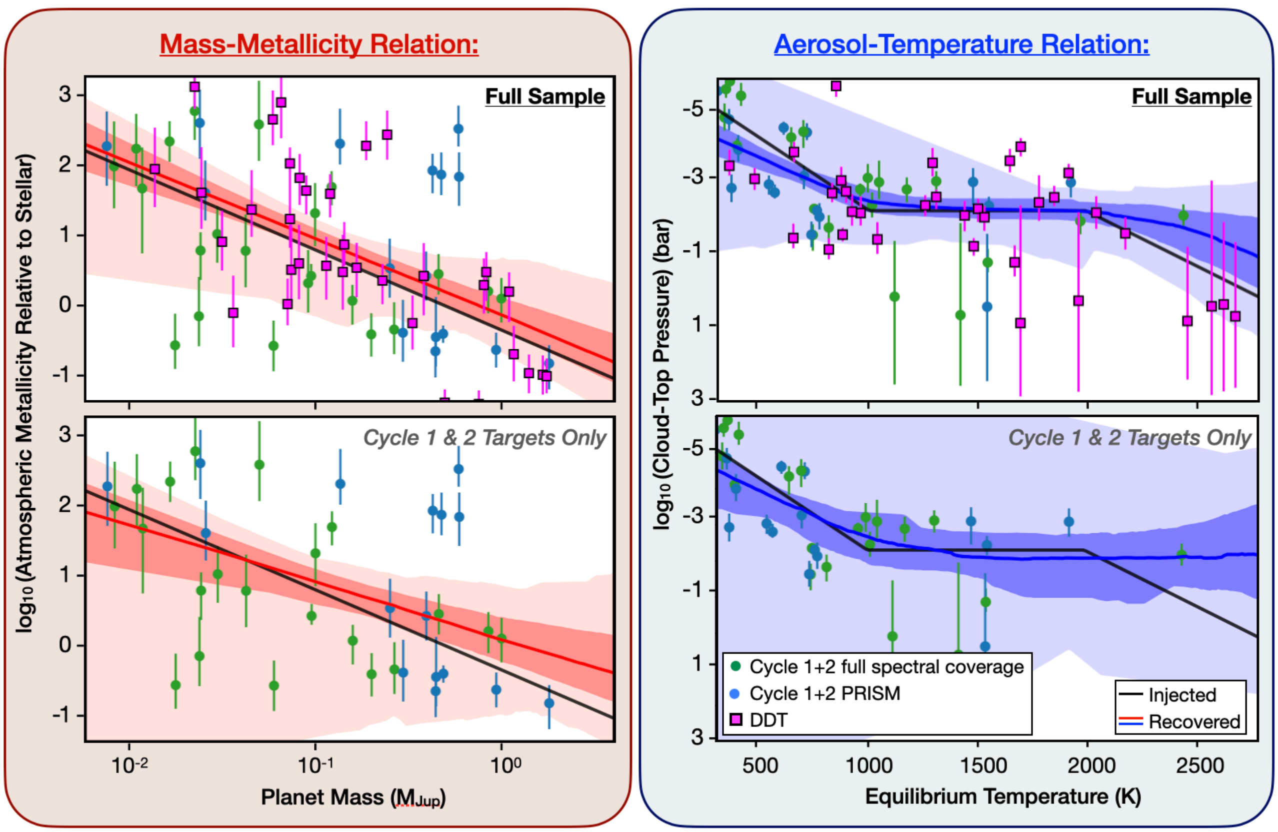

Figure 2: Simulated population-level retrievals using the techniques of Lustig-Yaeger et al. (2022) to identify embedded trends in mass vs. metallicity and aerosol properties vs. equilibrium temperature. The trends are poorly identified from Cycle 1 & 2 observations alone (i.e. the slope of the mass-metallicity relation and transitions in aerosol properties are not confidently recovered, given the intrinsic spread in atmospheric properties). The addition of the DDT data allows for robust recovery of these population-level trends (and presumably many others that we have not explicitly modeled) by filling in critical regions of parameter space that are missed by the GO programs.