Temperate sub-Neptunes as a window on habitable worlds and the early Earth

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:

The atmospheres of temperate sub-Neptunes (with $T_{eq} < 400$ K) are fantastic laboratories for understanding photochemistry, the formation of water cloud and interior-atmosphere interactions that occur on habitable planets, in particular in their early phases. They could even provide a window on the origin of life on Earth, and some temperate sub-Neptunes could be habitable with a liquid water ocean. Investigating all these fundamental processes requires deep atmospheric characterization of a sample of temperate sub-Neptunes. We propose to complete observations of JWST cycles 1 & 2, with NIRISS/SOSS, NIRSpec/G395 and MIRI-imaging, for a list of targets: L 98-59 d, LP 791-18 c, TOI-270 d, TOI-1231 b, LTT 3780 c, TOI-1468 c, LHS 1140 b and K2-18 b. The accumulated transits/eclipses would enable: 1) robust detections of HCN, H_2O, CO, CH_4, NH_3 and CO_2, 2) a search for minor chemical species, 3) planetary albedo measurements, 4) constraints on cloud/haze altitude, optical properties and variability.

Anticipated Science Objectives: Temperate sub-Neptunes (with $T_{eq} < 400$ K) are prime targets for understanding key atmospheric processes controlling the habitability of exoplanets and the early Earth before the appearance of life (∼4 Ga):
1) Atmosphere-interior interaction and ocean formation. Recent studies suggest the formation of water through the interaction between hydrogen-rich primary atmospheres and underlying magma oceans, possibly at the origin of Earth's oceans [1, 2]. This could be tested by JWST measurement of the water content and the C/O ratio [1].
2) Photochemistry and prebiotic chemistry. The early Earth could have had a transient H_2- and CH_4-rich atmosphere, leading to organic haze and prebiotic molecules as HCN at the origin of life [3]. Probing the chemical composition (i.e. HCN and organic molecules, see [4]) and haze of temperate sub-Neptunes could thus constrain the prebiotic chemistry of the early Earth.
3) Water clouds and habitability. Transits and eclipses could reveal water cloud formation, location (day or night side) and albedo [5], with strong implications for the formation of water oceans on rocky planets [6, 7], including Earth and Venus. Finally, some sub-Neptunes could be habitable with a water ocean [8, 9].
Target list and strategy for DDT observations. We propose transit observations with NIRISS and NIRSpec/G395 (objectives 1 & 2) and MIRI eclipses (objective 3) of a sample of planets. By order of priority (based on TSM): L 98-59 d, LP 791-18 c, TOI-270 d, TOI-1231 b, LTT 3780 c, TOI-1468 c, LHS 1140 b, K2-18 b. Transits are planned for JWST cycle 1 or 2 for all these planets. A large number of transits (typically 5-10, see table 1) should be accumulated for these targets. LP 791-18 c is ideal for eclipses. K2-18 b is promising for cloud variability with NIRISS. LHS1140 b is a prime target for habitability.

Urgency/Timeliness: The nature and formation of sub-Neptunes is a major question. Temperate sub-Neptunes are a necessary step before temperate rocky planets. Due to the relatively relatively long orbital periods, observations must begin early to accumulate a sufficiently large number of transits.

Risk/Feasibility: Temperate sub-Neptunes are excellent targets (TSM ∼10-20× higher than rocky planets) and they are relatively haze-free [10].

Cannot be accomplished in the normal GO cycle: The aim is to perform a survey and a deep characterization on high-value targets, completing observations from cycle 1 and 2. This require a lot of time (∼100h for the first 5 planets, ∼80h for LHS1140 b) and to adapt the target list based on results from cycles 1 and 2.

Planet	$T_{eq}(K)$	TSM	ESM	Number of transits in cycles 1 & 2	Additional transits required for DDT
L 98-59 d	419	300	4.4	2 NIRISS + 1 G395	1 G395
LP 791-18 c	354	166	3.3	1 NIRISS + 1 LRS	3 G395 + 4 MIRI-imaging eclipses
TOI-270 d	387	132	2.2	1 NIRISS + 2 G395 + 1 LRS	1 G395
TOI-1231 b	328	109	1.8	1 NIRISS + 1 G395 + 1 LRS	2 G395
LTT 3780 c	362	103	1.9	1 NIRISS + 1 G395 + 1 LRS	1 NIRISS + 4 G395
TOI-1468 c	336	77	1.1	1 NIRISS + 1 G395 + 1 LRS	2 NIRISS + 5 G395
LHS 1140 b	234	63	0.2	1 G295 + 1 G395	4 NIRISS + 9 G395
K2-18 b	278	49	0.3	1 NIRISS + 2 G295 + 5 G395 + 1 LRS	2 NIRISS + 5 G395

Table 1: Target list of temperate sub-Neptunes with number of transits (for NIRISS/SOSS, NIRSpec/G295, NIRSpec/G395 and MIRI/LRS) observed during cycle 1 & 2. The last column gives the additional required transits to enable robust detections of HCN, H_2O, CO, CH_4, NH_3 and CO_2 for a 300×solar metallicity. Values are scaled from estimations for K2-18 b from [4]. Eclipses would be done with MIRI-imaging with filters F1280W and F1500W.

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