Witnessing the Evolution of Sub-Neptunes

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:

In this white paper, we advocate for a large survey of young sub-Neptune ($R_p = 2.5 - 6R_\oplus$) progenitors, orbiting GKM stars. There are two leading hypotheses regarding the formation of this class of exoplanet. One possibility is that volatile enriched progenitors form at or exterior to the H_2O condensation ("snowline") and subsequently migrate inwards. Alternatively, if the progenitor core formed interior to the H_2O snowline via pebble accretion — the resulting sub-Neptune being depleted in volatiles. The formation pathway and level of volatile depletion of sub-Neptunes remain open questions because the majority of extant HST transmission spectra of mature (> 1 Gyr) sub-Neptunes are featureless. Surveying a population of 25-750 Myr aged sub-Neptunes will inform our understanding of the formation pathway and atmospheric evolution of these planets. The lower age limit is set by the current population of young planets. We advocate for a dozen targets to be observed twice with NIRISS/SOSS and NIRSpec/G395H (~ 500 hours). Additionally, we advocate for simultaneous HST/COS observations to characterize the FUV output of the host stars, a critical input for understanding atmospheric chemistry and haze formation. We note that although **young transiting exoplanets** provide a critical window to differentiate formation pathways, they represent only **3% of all transiting planets to be observed with JWST before the start of Cycle 3.**

Atmospheric compositional measurements in sub-Neptune progenitors will provide critical information to distinguish between their formation pathways. Empirical volatile contents will distinguish between formation pathways involving core formation exterior [1, 2, 3] or interior to the H_2O snowline [4, 5, 6]. This proposed survey of a dozen sub-Neptunes orbiting GKM stars would provide abundance measurements of H_2O and elemental ratios (Fig. 2). Existing HST observations of mature (>1 Gyr) sub-Neptunes have provided **little compositional information** for this ubiquitous population [7, 8, 9, 10], presumably due to high-altitude hazes [Fig. 1; 11]. Meanwhile, HST observations of V1298 Tau b (~ 30 Myr) has a **haze free atmosphere** [12]. Observations of sub-Neptune progenitors would constrain the **atmospheric composition** of otherwise featureless mature sub-Neptunes.

These objectives are achievable with a population survey with NIRISS/SOSS and NIRSpec/G395H (0.5 - 5 μm), where the NIRISS observations will help constrain the transit light source (TLS) effect [13]. Two observations per instrument per planet are required for a statistically significant detection of features because of variable high-energy stellar irradiation which modulates local planetary environments [14]. Given this, and the varying levels of TLS effects from transit-to-transit, simultaneous FUV observations per transit will help constrain the activity and provide critical insights into atmospheric chemical measurements [15].

While stellar activity will be a challenge, we will gain insights **beyond** exoplanet science, into (I) starspot coverage fraction and temperatures; (II) stellar interiors; (III) IR stellar flares for young stars. This survey will answer Astro2020 Decadal Survey questions: "What Fundamental Planetary Parameters and Processes Determine the Complexity of Planetary Atmospheres?" and "How Does a Planet's Interaction with Its Host Star and Planetary System Influence Its Atmospheric Properties over All Time Scales?"

Urgency: There is no homogeneous sample of young planetary transmission spectra to statistically understand planet formation and evolution. Risk/Feasibility: While these planets do not have masses, HST/WFC3 (GO 16462) and JWST (GO 2149, 2498) have observed transmission features from young planets, contrary to their featureless mature counterparts (Fig. 1). Timeliness: This survey is relevant for understanding the mature population of exoplanets already observed with JWST. Incompatibility with GO cycle: This survey requires HST observations to characterize the FUV environment to interpret photochemistry and cloud formation. Here, the use of HST is an ancillary objective, whereas joint programs requires the HST time to be critical to the primary objective.

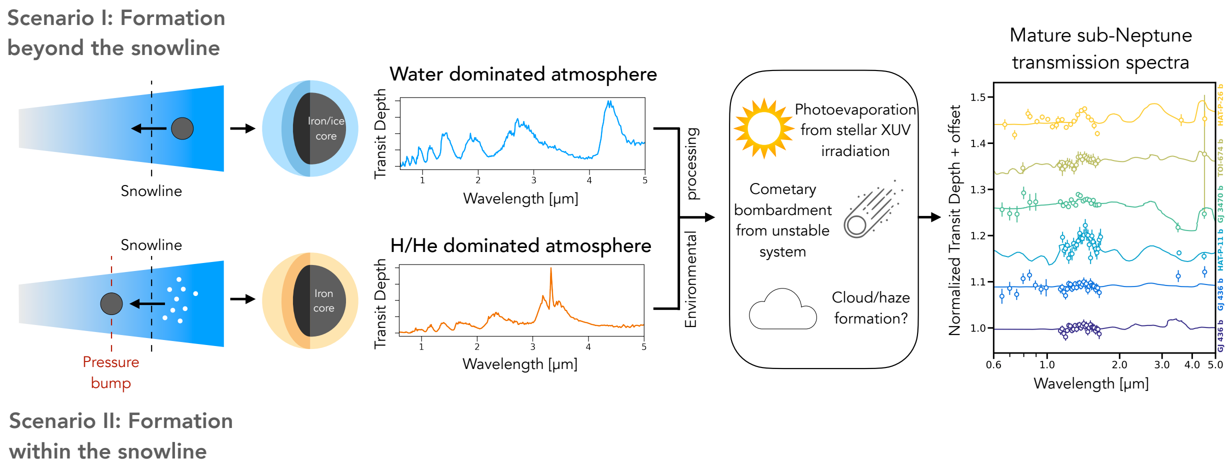

Figure 1: The differences in atmospheric compositions for sub-Neptunes which formed beyond or interior to the H_2O snowline. Simulated transmission spectra per scenario for *young* sub-Neptune progenitors are included. As these planets evolve, they undergo processing from their environments. While some HST spectra (right) show tentative evidence of H_2O, many targets in this planetary demographic have featureless spectra. With a survey of young sub-Neptune progenitors, we will shed light on the true formation mechanism for these ubiquitous planets.

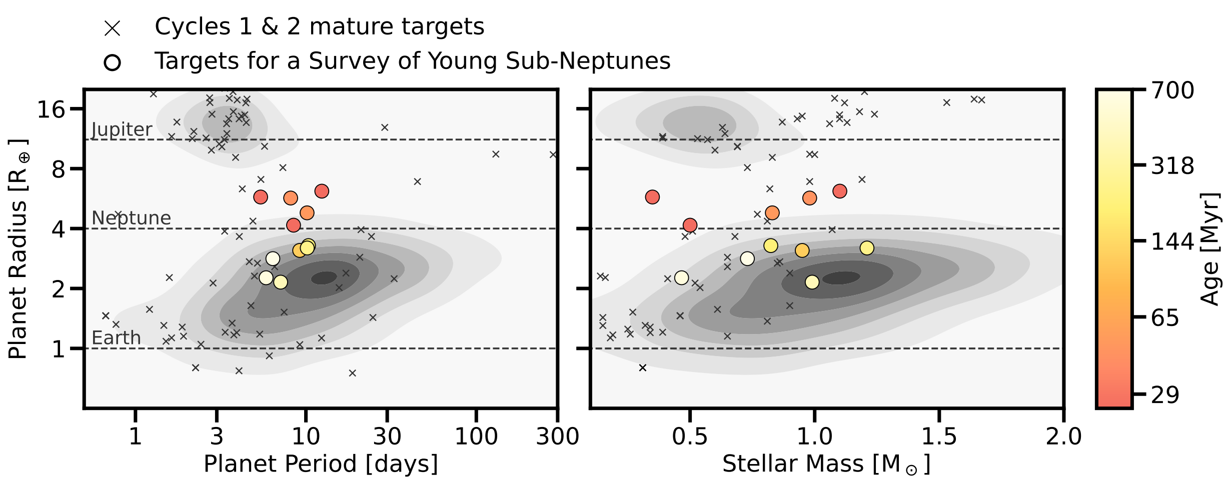

Figure 2: Period-planet radius (left) and a host star mass-planet radius (right) diagrams highlight the unique system properties of a proposed young to intermediate aged sample of sub-Neptune progenitors orbiting GKM stars (circles) with respect to the older *Kepler* planets (gray contours, indicating planet occurrence). Mature transiting exoplanets observed during JWST Cycles 1 and 2 are shown as x's. The very youngest systems ($< 100\,$Myr) have properties in a sparse region of parameter space. Ongoing XUV observations of young host stars indicate these planets ($R_p > 4R_\oplus$) could evolve down to $\sim 2R_\oplus$ [16]. The proposed sample has several direct analogues in the mature sample already observed. Thus, this proposed initiative will significantly advance our understanding and interpretation of current JWST targets.

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