The first search for a surface ocean on a sub-Neptune to increase prospects for habitability

Abstract:

Hycean planets are a new, theorized class of potentially habitable planets. These worlds are water-rich sub-Neptunes (2 – 4 R_{Earth}) with liquid surface oceans underneath a small H_2-dominated atmosphere. The larger physical size, and larger atmosphere of Hycean planets make them easier to characterize than terrestrial planets. Also, a liquid ocean on a Hycean world is physically possible for a wider range of planetary sizes, masses, and radiation environments than is possible on a terrestrial planet, which greatly expands the region of parameter space that may be habitable. However, very little is known about the nature of these planets, if they exist in nature at all, as only one planet in the theorized Hycean regime has received any atmospheric observations. We propose to spectroscopically observe the Hycean-regime sub-Neptune K2-18b using JWST/NIRSpec. JWST's unique combination of wide spectral range and unprecedented precision will enable us to probe for the presence of a surface ocean on K2-18b via its influence on the atmospheric composition. These observations will: (1) enable the first ever inference of a surface on a sub-Neptune planet; and (2) definitively answer whether Hycean planets are real or fiction. This program will transform conceptions of habitability in the Galaxy and inform new observational strategies in the upcoming JWST era.

Science Justification

Hycean planets have the potential to transform the search for habitable planets.

Hycean planets are hypothetical water-rich sub-Neptunes that host water oceans on their surface, underneath their H_2-rich atmosphere (Madhusudhan et al. 2021). Interior structure models show that deep oceans of liquid water can stably exist on these planets' surfaces for a wide range of planet masses (M $\leq 10\ M_{Earth}$), radii (R $\leq 2.6\ R_{Earth}$), temperatures (T $\leq$ 700 K), and atmospheric surface pressures (P $\leq 10^4$ bar) (Madhusudhan et al. 2021, Nixon et al. 2021). In comparison, terrestrial planets can only host liquid water on their surface at a far more limited range of planetary sizes and temperatures. If Hycean planets exist as theorized, these planets greatly expand the region of parameter space that is potentially habitable.

The surface ocean on a Hycean planet cannot be directly probed. The large H_2-rich atmosphere that supports this ocean also shrouds it from outside observers. Fortunately, the surface ocean is detectable through its influence on the atmosphere's composition. The presence of a surface at moderate pressures (P $\leq 10^4$ bar) blocks thermochemical recycling of molecules into a deep, hot atmosphere. This leads to changes in the equilibrium abundances of molecules relative to an atmosphere with no surface (Yu et al. 2021). In the particular case of a surface water ocean, the abundances of CO_2 and *CO* are enhanced, while NH_3 and *HCN* are depleted (Hu et al. 2021). <u>The abundances of these molecules can be probed by JWST/NIRSpec,</u> making Hycean oceans detectable through atmospheric observations with current technology.

<u>However, no sub-Neptune has been sufficiently characterized to confirm the presence of a surface ocean</u>. As a result, it is uncertain whether any Hycean planets exist in nature. Several sub-Neptunes are known within the proposed Hycean mass, radius, and temperature regime, but the atmospheric characterization necessary to confirm if they truly are Hycean planets was not possible until JWST. Hycean planets can open a wider parameter space of parameters for habitability and have relatively favorable properties for characterization compared to terrestrial planets. As such, the confirmation of Hycean planets will directly advance the JWST's key science goal to identify and characterize potentially habitable planets.

We propose to spectroscopically observe 4 transits of the Hycean candidate K2-18b using NIRSpec G235H and G395H. These filters cover prominent transmission features of CO_2, CO, NH_3, and HCN between 1.66 – 5.1 microns. <u>With these observations, we will constrain the abundances of these surface-tracing gases to +/- 1.5 dex, and detect the presence of K2-18b's surface at >3-sigma.</u> These observations will be the first ever investigation of a surface on a sub-Neptune, and directly test whether Hycean planets exist. Our findings will have profound implications on the search for potentially habitable exoplanets, and expand our understanding of what planetary environments are habitable.

Hycean planets may have already been found, but current data cannot confirm their existence

To date, 1869 sub-Neptune exoplanets have been confirmed (NASA Exoplanet Archive). Of these, ~40 lie within the proposed Hycean mass and radius regime (Madhusudhan et al. 2021). However, mass and radius alone cannot tell us about the planet's composition since several different combinations of interior and atmospheric compositions can yield the same mass and radius (e.g. Madhusudhan et al. 2020). Atmospheric characterization is direly necessary to reveal the planet's composition and structure, both in the atmosphere and at the surface.

JWST observations will begin this year with the goal of identifying potentially habitable planets, making this investigation timely. Figure 1 shows how the habitable zone (HZ) for Hycean planets is ~10x wider than the terrestrial HZ. Finding a potentially habitable planet will be easier when searching within a wider parameter space. More planets are currently known to reside within the Hycean HZ than the terrestrial HZ, offering plenty of targets for JWST observations. Furthermore, Hycean planets generally have a higher Transmission Spectroscopy Metric (TSM) than terrestrial planets (Kempton et al. 2018), owing to their larger radii and larger allowed temperatures. The TSM is a metric for ranking a planet's potential for good signal-to-noise atmospheric characterization. Confirmation of whether Hycean planets exist will better enable JWST to fulfill its science goal of finding a potentially habitable exoplanet. <u>Our transmission spectrum of K2-18b will provide this very first direct confirmation of a Hycean planet.</u>

K2-18b is a readily characterizable Hycean candidate

K2-18b is a sub-Neptune in the habitable zone around its host star. K2-18b's mass (8.6 ± 1.4 M_E) and radius (2.51 ± 0.15 R_E) (Cloutier et al. 2019, Hardegree-Ullman et al. 2021) place it at the upper edge of the proposed Hycean mass-radius regime (Madhusudhan et al, 2021), as shown in Figure 2. Therefore, K2-18b is a candidate Hycean planet, and thus provides a direct test of whether Hycean planets exist.

Of the known Hycean candidates, K2-18b's cool temperature (T = 250 K) and previous characterizations make it the best initial target. Together, these provide evidence that clouds and/or hazes in K2-18b's atmosphere will not block atmospheric characterization. Clouds and hazes are known to mute, or completely flatten spectral features in sub-Neptune atmospheres (e.g. on GJ 1214b: Kreidberg et al. 2014). Recent modeling, however, suggests that clouds and hazes are less impactful on cooler planets with temperatures less than ~500 K, and their effect decreases with decreasing temperature (Dymont et al. 2021, Yu et al. 2021b). At T = 250 K, K2-18b should therefore be relatively cloud-free. In addition, previous HST/WFC3 transmission spectroscopy observations have detected water in K2-18b's atmosphere (Benneke et al. 2019). This water detection shows that K2-18b's transmission features are detectable. This suggests that K2-18b's atmosphere is indeed free of significant clouds and hazes. Therefore, K2-18b is directly accessible to atmospheric characterization with JWST, and is a prime first target for testing Hycean candidates.

A NIRSpec transmission spectrum can directly infer K2-18b's surface.

With NIRSpec G235H and G395H, we will measure K2-18b's transmission spectrum between 1.66 – 5.1 μm. This wavelength range covers prominent spectral features for carbon- and nitrogen-bearing species including: CO, CO2, NH3, and HCN, which are direct tracers of whether the planet's atmosphere interacts with a surface. Figure 3 shows simulated transmission spectra of K2-18b, from Hu et al. 2021.

Our NIRSpec spectrum includes three regions with which we can distinguish K2-18b having a surface: (a) the NH_3 and CO_2 features near 2 μm; (b) the HCN and C_2H_2 features near 3 μm; and (c) the CO_2 and CO features between 4-5 μm. Based on our calculations with the observation simulator PandExo (Batalha et al. 2017), we expect to achieve a transit depth precision of 20 ppm when binning our 4 combined spectra to a resolution of R~100. With this precision, we can distinguish between the surface and no-surface cases across the three regions at >3-σ. We will also run our observed spectrum through an atmospheric retrieval, using which we will constrain the abundance of each molecule to ±1.5 dex. These constraints will help determine if K2-18b's surface, if present, has an ocean. In particular, we expect to see an enhanced atmospheric CO_2 and CO abundances if the surface is an ocean, versus solid rock and ice.

<u>Our observations will therefore allow us to detect K2-18b's surface at >3-σ significance, and infer if that surface is a water ocean.</u> As a result, we will be able to confirm whether K2-18b is a Hycean planet.

K2-18b has the potential to anchor our understanding of sub-Neptunes, and revolutionize the search for habitable planets

Our proposed observations will be the first empirical investigation of a surface on a sub-Neptune planet. This investigation will provide a well needed benchmark for interior modeling of sub-Neptunes, for which the location and properties of the planet's surface are currently unconstrained. This benchmark will be key to interpreting JWST observations of sub-Neptunes over the next decade and beyond.

Our observations also have profound implications for astrobiology and the search for life. JWST's key science goals include understanding the suitability of exoplanets as habitats, and studying planets in their star's habitable zones. Our proposed observations will tackle these goals directly by making the first test of whether Hycean planets exist. If Hycean planets do exist, they will transform the search for habitable planets. Hycean planets can be habitable for a wider range of radii, masses, and temperatures than terrestrial planets (Madhusdhan et al. 2021). Also, Kepler statistics suggest that sub-Neptunes are more common than terrestrial planets (Fulton & Petigura 2018), which would lead to a greatly increased sample size of potentially habitable targets if Hycean planets are added to the mix. If K2-18b is indeed Hycean, then our observations will furthermore provide the first detailed atmospheric characterization of a Hycean planet. This will enable in-depth modeling of K2-18b's habitability, and expand the scope of astrobiology to sub-Neptune planets. Our work has the potential to solidify JWST's legacy in studying habitability beyond Earth early on its mission.

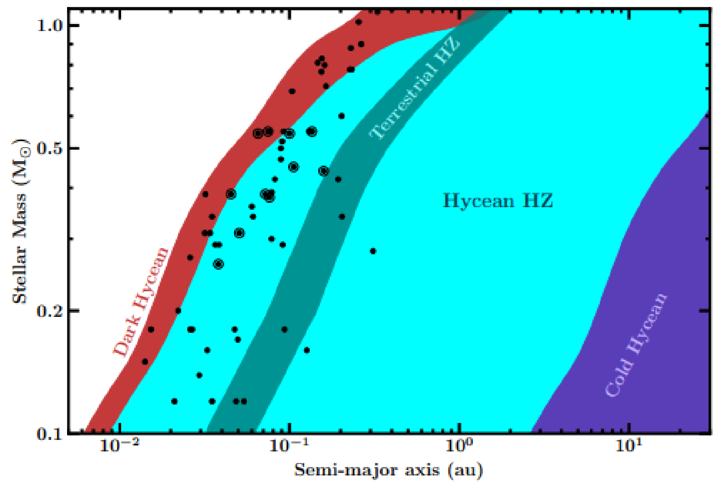

Figure 1: The extent of the habitable zone (HZ) for Hycean planets, in terms of stellar mass and the planet's semi-major axis. Also shown for comparison is the HZ for terrestrial planets. Black points represent known planets with the right mass, radius, and temperatures to be considered habitable in their corresponding HZ, including our target K2-18b. *Confirmation of K2-18b being a Hycean planet will open up the search for a potentially habitable exoplanet to a ~10x wider range of potentially habitable parameter space.* Figure taken from Madhusudhan et al., 2021.

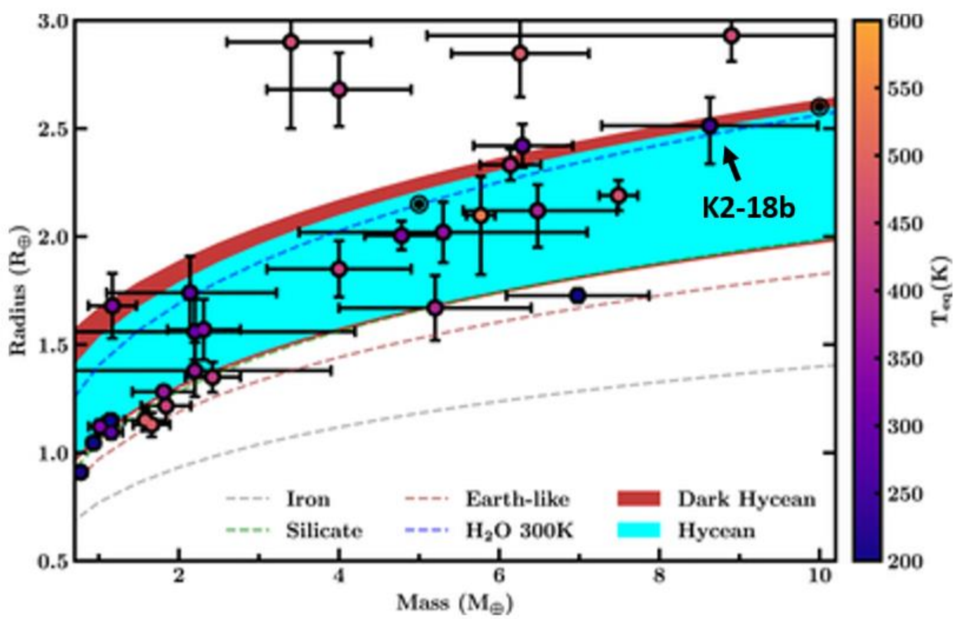

Figure 2: Mass and radius diagram showing our target K2-18b among other known Hycean candidates. K2-18b lies near the edge of the Hycean mass-radius regime, defined by Madhusudhan et al. 2021. Also shown via the colorbar is each planet's temperature. Of these Hycean candidates, K2-18b is the coolest, which favors the atmosphere being free of significant clouds and hazes. *As a result, K2-18b's atmosphere can be readily characterized.* Figure taken from Madhusudhan et al. 2021

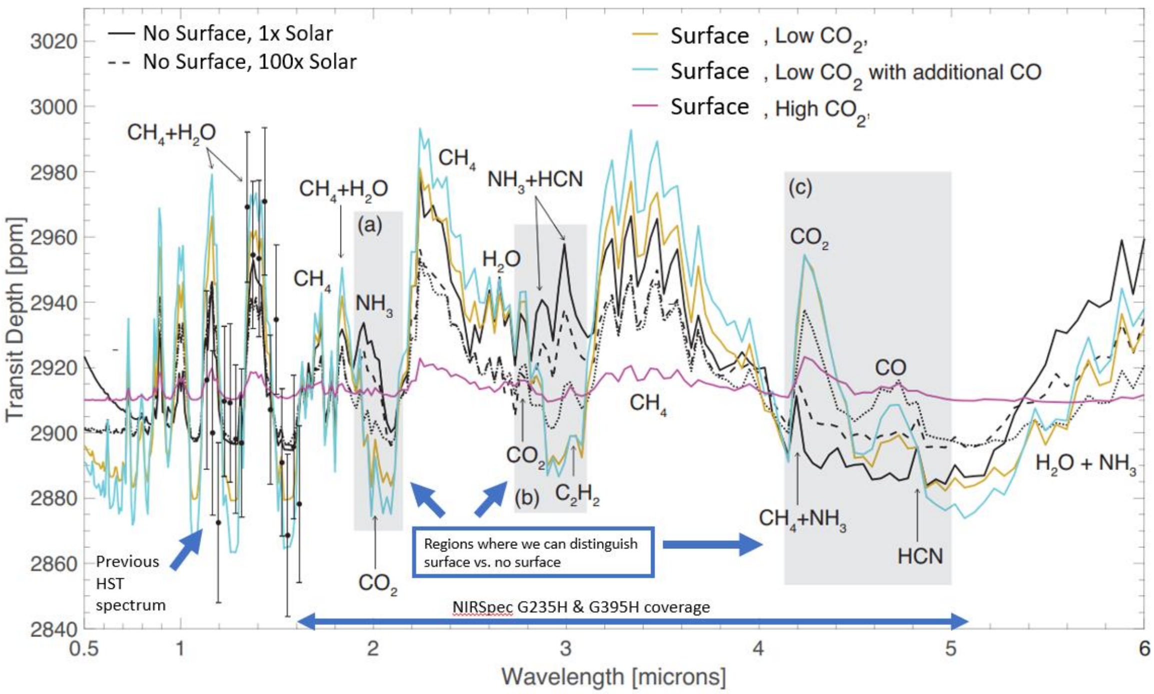

Figure 3: The solid and dotted black curves represent the planet having no surface, and thus a massive, thermochemically recycled atmosphere. The solid colored curves represent a planet with a surface, which interacts with a small, bottom-bounded atmosphere. Also shown are the previous HST observations of K2-18b [Benneke et al. 2019]. Within the wavelength range of NIRSpec, there are three primary windows in which we can distinguish between these scenarios at >3-sigma, assuming a transit depth precision of 20 ppm. *With the proposed observations (gray shaded regions), we can infer the presence of K2-18b's surface at >3-sigma.* Figure adapted from Hu et al. 2021.

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