Identifying rocky planets and water worlds among sub-Neptune-sized exoplanets with the Habitable Worlds Observatory

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Astronomers are debating whether the plentiful “sub-Neptune” exoplanets – worlds a bit larger than Earth but smaller than Neptune – are predominantly rocky planets, water-rich “ocean worlds,” or gas-enshrouded mini-Neptunes. This question is crucial because such sub-Neptune-sized planets are among the most common in our galaxy, yet we have no analog in our own solar system, making them a key to understanding planet formation and diversity. It also directly impacts the search for habitable worlds: larger-than-Earth planets with solid surfaces or oceans could support life, whereas gas-rich mini-Neptunes likely cannot. However, distinguishing these types using only a planet’s mass and radius is very challenging, because different compositions can produce similar densities, leaving a world’s nature ambiguous with current data. The proposed Habitable Worlds Observatory (HWO), a future NASA flagship telescope, offers a solution. HWO could directly image and spectroscopically analyze starlight reflected from $50 \sim 100$ sub-Neptunes around nearby stars, aiming to reveal their atmospheric compositions and potential surfaces. Using visible and near-infrared spectroscopy along with sensitive polarimetry, HWO would detect atmospheric gases (such as water vapor, methane, and carbon dioxide) and search for telltale surface signatures, including rock absorption features and the characteristic reflectivity patterns of oceans. By analyzing these signals, we could determine whether sub-Neptunes are large rocky planets or water worlds rather than gas-dominated mini-Neptunes. Crucially, expanding the search beyond Earth-sized planets to include these abundant sub-Neptunes may uncover entirely new classes of potentially habitable worlds, directly advancing HWO’s mission to identify and characterize planets that could support life.

1. Science Goal

The fundamental question we aim to address in this HWO science case is: **At what frequency do nearby stars host rocky planets or water worlds versus mini Neptunes with gaseous envelopes?**

The exploration of exoplanets has revealed a staggering diversity of planets beyond the solar system. We have

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discovered > 6000 validated exoplanets in our interstellar neighborhood, and most of the planets for which we have measured radii are within 3 times Earth's radius (NASA Exoplanet Archive). In addition to a small subset of Earth-sized planets, many more discovered planets have radii in the 1.4 – 2.6 Earth radius range, covering a planet size range not found in the solar system (Fulton & Petigura 2018). Current observations and models suggest that these larger-than-Earth planets can have either a predominantly rocky composition (commonly referred to as "super-Earths") or substantial volatile-rich layers (commonly referred to as "sub-Neptunes"). Meanwhile, the planet demographics and the planet formation models indicate that sub-Neptunes can be either planets with massive H_2/He/H_2O envelopes or planets with a large fraction of water by mass and without any massive H/He layer (sometimes referred to as "water worlds" or "ocean planets"; Figure 1; Venturini et al. 2020; Izidoro et al. 2022; Luque & Pallé 2022; Rogers et al. 2023; Burn et al. 2024; Benneke et al. 2024; Hu et al. 2025).

It is currently unknown whether most sub-Neptunes are gas dwarfs or water worlds, and how their composition depends on bulk planetary properties and formation and evolution environments. Therefore, determining the composition of sub-Neptunes is one of the frontiers of exoplanet science today. For transiting sub-Neptunes typically in close-in orbits of stars, astronomers are pursuing their nature by obtaining precise measurements of their masses and radii, as well as measuring their atmospheric composition using HST and JWST (e.g., Madhusudhan et al. 2023; Damiano et al. 2024; Piaulet-Ghorayeb et al. 2024). ESA's PLATO and ARIEL missions may detect and characterize more transiting sub-Neptunes in the next decade.

The characterization of sub-Neptunes through transit has been and will be limited to those planets in close-in orbits. Because most rocky planets, water worlds, and gas dwarfs in the habitable zones and wider orbits of FGK stars do not transit, they will remain elusive with current facilities. The distinction between gas dwarfs and water worlds is crucial for low-temperature planets in wide orbits (i.e., the planets typically probed by the Habitable Worlds Observatory), because the temperate water worlds that have moderate-size ($<\sim$ 50 bars) atmospheres can host liquid-water oceans even though they are not Earth-like rocky planets (Goldblatt 2015; Koll & Cronin 2019; Madhusudhan et al. 2021; Hu et al. 2021). It is thus essential to be able to distinguish rocky planets and water worlds from gas-rich planets for the search for habitable worlds.

This science case addresses the Questions and Discovery Areas E-Q2b, E-Q2c, and E-Q3b identified in the Astro2020 decadal survey final report.

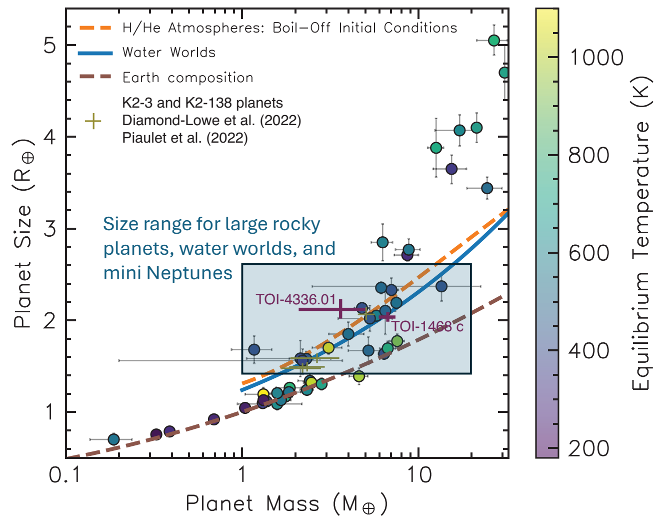

Fig. 1.— Diverse density and composition of small exoplanets. The plot shows M-dwarf planets that have precision mass and radius measurements (Luque & Pallé 2022). Small planets of FGK stars also occupy a broad parameter space that spans from Earth composition to water worlds or planets with massive H/He envelopes (Parc et al. 2024). The planets in the 1.4 – 2.6 Earth's radius range can be large rocky planets, water worlds, or having massive H/He envelopes (Luque & Pallé 2022; Rogers et al. 2023). The figure is adapted from Rogers et al. (2023) with permission.

2. Science Objective

Our science objective is to characterize the atmospheres and surfaces of the exoplanets discovered to the extent that distinguishes planets with massive H_2/He envelopes, planets with massive H_2O-dominated envelopes, and rocky planets with secondary atmospheres.

The current exoplanet demographics and characteristics, if extending to long-period planets (the main group of planets to be discovered by HWO), imply that HWO could detect approximately 5 times as many larger-than-Earth planets as Earth-sized planets (e.g., LUVOIR Team et al. 2019). The larger-than-Earth planets will likely include large rocky planets, water worlds, and mini Neptunes (Figure 1). Moreover, the planets to be discovered by HWO are even more likely to be water worlds than planets discovered by Kepler or TESS (and in the future by PLATO), because they are generally farther from their host stars, and thus form closer to the ice line and should accrete significant quantities of water-rich solids (Bitsch et al. 2021). Identifying these temperate water worlds could provide a new avenue to find potentially habitable planets having liquid-water oceans.

JWST (and ARIEL in the future) can be used to determine the nature of transiting sub-Neptune-sized exoplanets, and Extremely Large Telescopes (ELTs) on the ground may measure the reflected light spectra of non-transiting sub-Neptunes. However, most of the viable targets of these observations will be in close-in orbits of M dwarf stars with few exceptions (e.g., Snellen et al. 2022). To determine the atmospheric properties of sub-Neptunes in or near the habitable zones of nearby stars will require direct imaging through a mission like HWO. In the meantime, any long-period transiting sub-Neptunes found by PLATO could be preferred targets for further characterization by HWO, as the radius of these planets would be known precisely through transit measurements (e.g., Rauer et al. 2014). If any directly imaged sub-Neptunes are accessible by both HWO and ELTs, the spectroscopic observations are likely complementary as the ELTs could cover a wavelength range redder to that of HWO.

Distinguishing rocky planets and water worlds from mini Neptunes will rely on characterizing their atmospheres. If we have perfect knowledge of a planet's radius, the rocky nature could be confirmed if the planet's mass is measured to a precision of $\sim$ 1 Earth mass (Figure 1). This translates to a radial-velocity precision of $\sim$ 8 cm s^{-1} for planets in the habitable zone of the median star in the target list considered for HWO. However, observations that consistently provide such precision have not been reached yet in astronomy, and may not be possible for many stars that are mildly active or above the Kraft break (e.g., Crass et al. 2021). Astrometry may provide another avenue to measure the planetary mass precisely (see another SCDD on astrometry led by S. Gaudi). More importantly, the planet's radius is degenerate with the albedo for the planets to be discovered by HWO, at least in single-band photometry. For example, a 1.7-Earth-radius planet may have the same flux as a higher-albedo 1.4-Earth-radius planet. Such a large uncertainty in the planet's radius would further complicate the determination of the rocky nature of the planet from the mass and radius alone. Meanwhile, multiband and spectroscopic measurements can improve the radius constraints through characterizing the planetary atmospheres and surfaces (e.g., Feng et al. 2018; Damiano & Hu 2021).

Mini Neptunes have H_2-dominated atmospheres that are at least 0.1-1% planet mass to be consistent with the apparent planet size, corresponding to a pressure of at least $10^3 - 10^4$ bars (Rogers et al. 2023). These massive atmospheres will maintain thermochemical equilibrium at depths for C, O, N, and S species (Fortney et al. 2020; Hu 2021). By contrast, rocky planets and water worlds will have smaller atmospheres with diverse compositions, dominated by H_2, H_2O, N_2, CO, CO_2, or O_2, controlled by exchange with an ocean or a dry surface underneath (e.g., Hu et al. 2021; Krissansen-Totton et al. 2021; Liggins et al. 2022). The composition of secondary atmospheres on rocky planets is ultimately dependent on the initial volatile inventory and planetary evolution. A rocky planet could also have volcanoes that emit sulfur gases into the atmosphere (Hu et al. 2013; Loftus et al. 2019) and have spectral features of lands which are distinctive from those of oceans (Hu et al. 2012; Cowan & Strait 2013; Barrientos et al. 2023). Therefore, by determining the bulk atmospheric composition and measuring the abundances of key carbon-, nitrogen-, and sulfur-bearing molecules in the atmospheres of the detected exoplanets, we can characterize their intrinsic nature and identify rocky planets and water worlds. In addition to atmospheric composition, detecting surface features like ocean glint, vegetation red edge, spectral features of different land types also provides multiple lines of evidence, useful for distinguishing rocky planets and water worlds.

3. Physical Parameters

To achieve the science objective, this science case aims to leverage HWO's capabilities to determine the dominant atmospheric gases and the abundances of key carbon-, nitrogen-, and sulfur-bearing molecules of 50 – 100 exoplanets that have a visible-wavelength planet-to-star flux ratio $< 10^{-9}$.

This science case is relevant to the planets that have a true radius ranging from 1.4 to 2.6 times Earth's radius. However, the true radius is not immediately known from direct-imaging detections and can be degenerate with the planetary albedo. By jointly fitting for the atmospheric state and radius, atmospheric retrievals can yield constraints on a planet's size. This, together with the constraints on the planet's mass (if available), will become an orthogonal measurement of the nature of the planets. Since we do not know the true radius a priori, we estimate that a 2.6-Earth-radius planet would have a planet-to-star contrast ratio at the quadrature phase of up to $\sim 10^{-9}$, and therefore propose the size cutoff in terms of the planet-to-star flux ratio. This quantity is not be confused with the required instrument contrast.

We do not specify the range of relevant planet-to-star distance or equilibrium temperature for this science case. This is because, in part, the range in which a sub-Neptune could sustain liquid-water oceans is still poorly understood. For example, a sub-Neptune having an H_2-dominated atmosphere could host liquid-water oceans at a planet-to-star distance that is well greater than the upper limit of the habitable zone defined for rocky planets (Kasting et al. 1993; Pierrehumbert & Gaidos 2011).

Due to the expected diversity of sub-Neptune-sized exoplanets, it is essential to build up a large enough sample

Table 1: Physical parameters of planets to be measured to achieve this science case.

Physical Parameter	**State of the Art**	**Incremental Progress**	**Substantial Progress**	**Major Progress**
Presence of gases in small exoplanet atmospheres	JWST is detecting H_2O, CH_4, CO, CO_2, NH_3, and SO_2 in transiting sub-Neptunes of M stars	Detection of H_2O in directly imaged sub-Neptune-sized exoplanets	Detection of H_2O, CH_4, and CO_2 in directly imaged sub-Neptune-sized exoplanets	Detection of additional gases such as CO, NH_3, HCN, H_2S, and SO_2 in directly imaged sub-Neptune-sized exoplanets
Abundances of the gases	JWST is measuring the abundances of H_2O, CH_4, CO_2, and SO_2 in transiting sub-Neptunes of M stars, sometimes to a precision of < 1.0 dex	Measuring the mixing ratio of H_2O to better than 1.0 dex in sub-Neptunes in directly imaged sub-Neptunes of FGK stars	Measuring the mixing ratio of H_2O, CH_4, and CO_2 to better than 1.0 dex in directly imaged sub-Neptune-sized exoplanets	Measuring the mixing ratio of additional gases such as CO, NH_3, HCN, H_2S, and SO_2 to better than 1.0 dex in directly imaged sub-Neptune-sized exoplanets
Dominant Atmospheric Gas	JWST is determining H_2- versus H_2O-dominated atmospheres on transiting sub-Neptunes of M stars	-	Determining whether directly imaged sub-Neptune-sized exoplanets have H_2-dominated atmospheres	Among non-H_2-dominated atmospheres, determining whether they are N_2-, H_2O-, CO-, CO_2-, or O_2-dominated
Number of planets characterized	0	5	50	100

to address population-level science questions. While initial characterization of a handful of targets could bring exciting science results on these individual planets, a sample of ~ 50 would allow us to determine the occurrence rates of large rocky planets versus water worlds or mini-Neptunes among sub-Neptunes by $> 3\sigma$ (assuming $> 20\%$ in the sample turns out to be rocky planets and $> 20\%$ water worlds). An enlarged sample of ~ 100 would provide unprecedented knowledge of how the formation of large rocky planets versus water worlds or mini-Neptunes depends on macroscopic parameters such as the mass and metallicity of the host star, concurrence of giant planets, and orbital separation and architecture, potentially redefining our understanding of the formation and evolution of habitable worlds.

The expected bulk atmospheric composition ranges from H_2-dominated to $N_2/H_2O/CO/CO_2/O_2$ dominated (e.g., Forget & Leconte 2014; Krissansen-Totton et al. 2021; Lichtenberg et al. 2023). The determination of a non-H_2 gas as the dominant (not just abundant) gas in the atmosphere strongly indicates the planets to be rocky planets or water worlds. If the dominant gas is found to be H_2, then determining whether the atmosphere has more abundant CH_4 or CO_2, as well as whether the atmosphere has abundant NH_3, will delineate whether the atmosphere is massive (indicating a mini Neptune) or not (indicating a rocky planet/water world) (Hu et al. 2021; Yu et al. 2021; Tsai et al. 2021; Wogan et al. 2024). If the atmosphere is found to be dominated by a non-H_2 gas, determining whether the atmosphere has volcanic gases such as SO_2 could further indicate whether the planet has a rocky surface (Loftus et al. 2019). As corroborating evidence, a low-temperature water world should not have abundant NH_3 in the atmosphere (Hu et al. 2021), although preferred partitioning of N and S in magmas could result in confounding scenarios (e.g., Suer et al. 2023; Shorttle et al. 2024). Furthermore, understanding the internal composition of the planets based on the stellar Fe, Mg, and Si composition (Schulze et al. 2021; Unterborn et al. 2023; Hinkel et al. 2024) could help delineate the rocky-planet versus water-world scenarios. The literature cited in this paragraph commonly indicates that using the abundances of the trace gases to infer bulk planetary properties will require a precision of $\sim$ 1.0 dex in the mixing ratio, which could be used as a guiding figure subject to further refinement.

4. Description of Observations

To achieve the measurements outlined above, HWO will need to conduct observations designed to measure the reflectance spectra of 50 – 100 exoplanets with a visible-wavelength planet-to-star flux ratio $< 10^{-9}$ from 0.25 to 1.7 μm, at a spectral resolution of $R > 140$, and SNR>10 per spectral element. These observations will leverage HWO's advanced capabilities in high-contrast imaging.

To detect a single gas (such as H_2O), spectroscopy in narrow ($\sim 20\%$) bands strategically placed in $0.6-1.0$ μm, with a spectral resolution of > 70 and SNR>10 per spectral element (defined at the continuum), would suffice (Latouf et al. 2023; Young et al. 2024). However, narrowband spectroscopy cannot precisely measure the mixing ratio of the gas due to the lack of sufficient out-of-band baseline and overall understanding of the context. Measuring the mixing ratio of H_2O to better than 1.0 dex and to distinguish a H_2O-rich atmosphere from a H_2O-dominated one will require spectroscopy that covers a broader wavelength range ($0.4-1.0$ μm) and with a higher spectral resolution of $R > 140$ (Feng et al. 2018; Damiano & Hu 2021, 2022).

Because H_2 itself does not absorb significantly in the wavelength bands expected to be covered by HWO (except, perhaps, the weak collision-induced opacity near $\sim$ 1.2 μm, Koroleva et al. 2024), to further determine whether the atmosphere is H_2-dominated or not could rely on (1) tallying the abundances of the main radiatively active components of the atmosphere (e.g., H_2O, CO_2), (2) inference from the chemical signature of the atmosphere (e.g., the CH_4-to-CO_2 ratio), and (3) inference from the Rayleigh scattering slope of the reflectance spectra. Method (1) is proven to be very hard because the reflectance spectra often lose dependence on the exact mixing ratio when the mixing ratio is above $\sim$ 1% for H_2O (Damiano & Hu 2021). We thus propose to aim at both (2) and (3) as they are complementary to each other. Method (2) would require measuring the mixing ratios of CH_4 and CO_2 to better than 1.0 dex, and this can be achieved by expanding the spectroscopy to the near-infrared wavelength range ($1.0-1.7$ μm) with a spectral resolution $R > 40$ and SNR>10 per spectral element (Damiano & Hu 2022). Method (3) could be achieved by measuring the reflectance spectrum precisely in visible light (SNR>20, Hall et al. 2023).

If a planet is found to not have a massive H_2 atmosphere, this opens up opportunities to further characterize its nature. (1) Is its atmosphere dominated by N_2, CO, CO_2, or O_2? (2) Does it have volcanic outgassing of H_2S and SO_2 as signposts of rocky planets? (3) Does it have a liquid-water ocean that can regulate the atmospheric abundance of CO_2 and dissolve any soluble gases such as NH_3, HCN, and SO_2? For (1), it has been shown that an SNR$\sim$40 in visible light is necessary to reliably break the degeneracy between an O_2-dominated versus an CO/N_2-dominated atmosphere, and because CO and N_2 have similar molecular weights, it is also necessary to observe the CO absorption feature at 1.6 μm (Hall et al. 2023). The O_2-O_2 collision-induced opacities in the near-infrared could help break this degeneracy for atmospheres larger than a few bars (e.g., Leung et al. 2020). For (2) and (3), low-resolution spectroscopy in the UV band ($0.25-0.4$ μm) can provide sensitivity to H_2S and SO_2 and their photochemical products, in addition to O_3 (Hu et al. 2013; Gao et al. 2017; Damiano et al. 2023). The detectability of NH_3 has not been assessed specifically for reflectance spectroscopy, but it has substantial absorption bands in $1.5-1.7$ μm. However, NH_3, CH_4, H_2O, CO, and CO_2 all have spectral features in the narrow wavelength range between 1.4 and 1.8 μm, and thus a higher spectral resolution in the near-infrared band is likely necessary to measure their mixing ratios. In addition, liquid and ice water clouds imprint characteristic signatures on the reflected light spectra in the near-infrared, particularly by modulating the continuum, which can be used to constrain cloud properties (e.g., Damiano & Hu 2022; Kofman et al. 2024; Roccetti et al. 2025). Direct detection of liquid-water oceans can be made by measuring the planetary phase curves and ocean glint (e.g. Cowan et al. 2009; Robinson et al. 2010; Lustig-Yaeger et al. 2018; Vaughan et al. 2023). Relevant measurements for direct detection of liquid-water oceans are discussed in a separate SCDD developed by N. Cowan, J. Lustig-Yaeger, and collaborators.

In addition, to break the degeneracy between an O_2-dominated versus an N_2- or CO-dominated atmosphere using the Rayleigh-scattering slope in the reflected light spectrum, it is necessary to have strong constraints on the planetary mass independently from the reflectance spectrum (Damiano et al. 2025) and achieve a high SNR (40) per spectral element in the visible wavelengths (Hall et al. 2023). It has been shown recently that a mass uncertainty of 10% would enable the spectral characterization of the bulk atmospheric composition (Damiano et al. 2025). See the SCDD developed by S. Gaudi and collaborators for an analysis of the feasibility of achieving such high-precision mass constraints via astrometry.

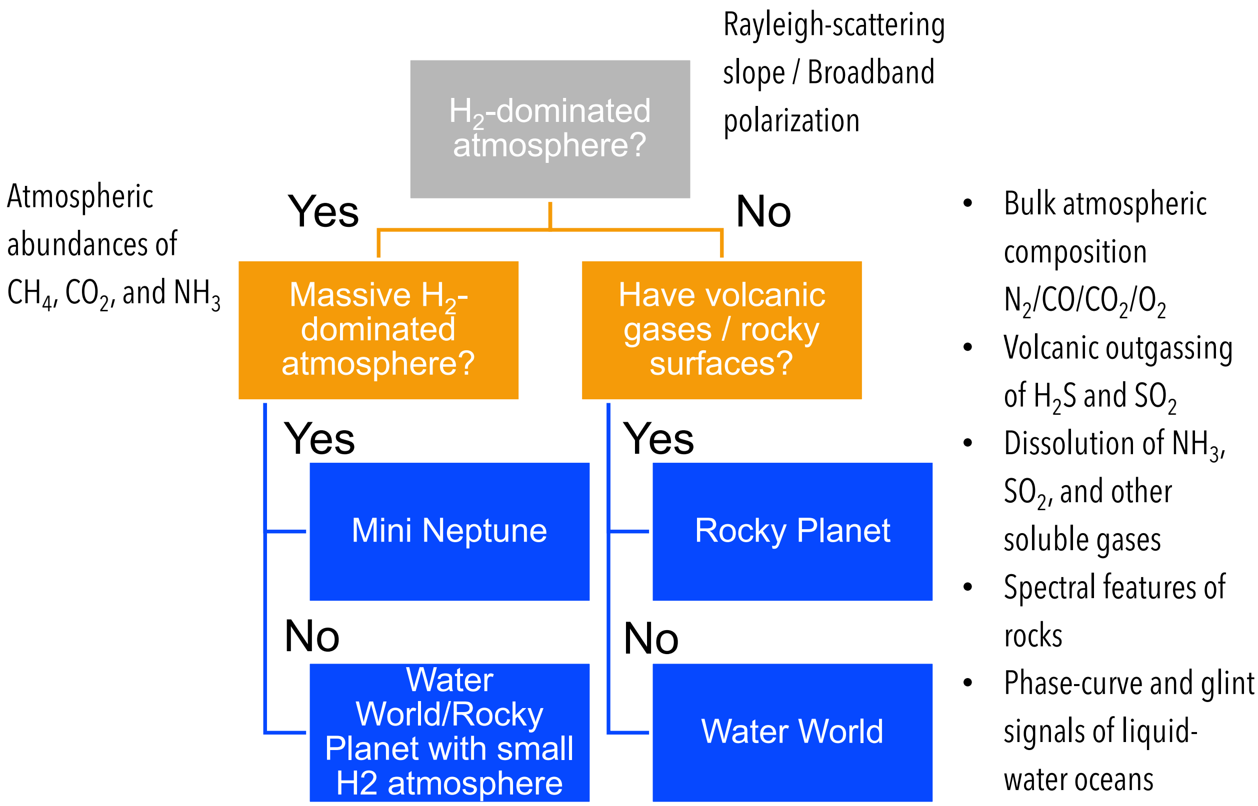

Fig. 2.— An observation and interpretation decision tree to characterize sub-Neptune-sized exoplanets via spectroscopy with HWO.

If a temperate planet is found to be a rocky planet or water world, it can conceivably host a liquid-water ocean. Then, the observations and measurements laid out in the previously-mentioned ocean detection SCDD should be applied, with the modification of the planet-to-star contrast ratio that could be as large as 10^{-9} in the visible band. We note that the actual flow of observations might differ from what is presented in this document, e.g., detecting a liquid-water ocean through glint or phase-curve signals might be easier than detailed spectroscopy for a subset of candidate planets. We identify this point to be an essential area for further study and optimization.

In addition, distinguishing between a planet with lands versus a planet fully covered by the ocean could also leverage the typical spectral features of lands in the visible and NIR bands (Hu et al. 2012; Barrientos et al. 2023). For candidate rocky planets, detecting spectral features of typical rocks (e.g., basalts, quartz, iron oxides, etc) provides a direct confirmation of their rocky nature. For reflectance spectroscopy with HWO, the most relevant spectral features come from electronic transitions of F^{2+} in the crystal fields of mafic rocks (such as olivine and pyroxene, absorbing broadly near 1 μm and 2 μm), typical absorption bands of bounded hydroxyl and water of hydrated rocks (at 1.4 μm and 1.9 μm), as well as reflectance slopes due to space weathering and oxidative weathering (Hu et al. 2012). The rock features and atmospheric features are potentially distinguishable thanks to their different spectral shape. Further studies are necessary to determine the exact spectroscopic measurements needed to achieve this feat.

Last but not least, polarimetry will be an invaluable tool in helping to distinguish between different types of planetary atmospheres and surfaces. In the 600–800 nm range, the peak degree of linear polarization can range from small values ($< 10\%$) for a rocky surface or a cloudy atmosphere, to very large values ($> 40\%$) for a Rayleigh scattering atmosphere. This wide range of conditions have readily been seen in the solar system in disk-integrated measurements and models: 6-10% for Moon, Mars, and Mercury, 30-50% for Neptune and Titan (in the Rayleigh-dominated portion of their spectra), and typically 5–10% for other giant planets and Venus. Earth, with its complex mix of a liquid surface, rocky ground, ice, vegetation, and a Rayleigh scattering atmosphere uniquely has a polarization

Table 2: Observations needed to achieve this science case.

Observations Needed	State of the Art	Incremental Progress	Substantial Progress	Major Progress
Reflectance spectroscopy of exoplanets with a planet-to-star flux ratio $<10^{-9}$	-	Spectroscopy in $0.4 - 1.0\ \mu$m with R>140 and SNR>10	Spectroscopy in $0.4 - 1.0\ \mu$m with R>140 and SNR>20, and spectroscopy in $1.0 - 1.7\ \mu$m with R>40 and SNR>10	Spectroscopy in $0.4 - 1.0\ \mu$m with R>140 and SNR>40, and spectroscopy in $1.0 - 1.7\ \mu$m with R>70 (to be refined) and SNR>10, and spectroscopy in $0.25 - 0.4\ \mu$m with R>7 and SNR>10
Broadband polarimetry in the reflected light of exoplanets with a planet-to-star flux ratio $<10^{-9}$	-	Single-band polarimetry with a precision of $\pm5\%$ at 2-3 epochs	Single-band polarimetry with a precision of $\pm3\%$ at 3-5 epochs	Multi-band polarimetry with a precision of $\pm1\%$ at 5-10 epochs
Number of planets characterized with a planet-to-star flux ratio $<10^{-9}$	-	5	50	100
Measuring the mass of the planets (mass ranging in 3 - 20 Earth mass)	-	-	Better than 3σ	Better than 10σ

in the 15-20% range (e.g., Gordon et al. 2023). Notably, orbital phase-resolved polarimetric measurements of Venus were used to identify sulfuric acid as the prime constituent of Venus's clouds (Hansen & Hovenier 1974).

While the polarization signal of the glint feature of a planet covered by liquid-water oceans is addressed in the separate ocean detection SCDD, broadband polarimetric measurements will more generally help distinguish the various types of small exoplanets laid out in this SCDD. Polarimetry is complementary to spectroscopy to diagnose the surface/atmospheric parameters because the polarimetric signals discussed above are all broadband features mostly in the visible wavelengths. In order to distinguish between the Rayleigh scattering dominated scenarios and an Earth-twin, a precision on the degree of polarization of $\sim \pm5\%$ would facilitate a 3σ distinction of the peak polarizations. In order to distinguish between an Earth-twin and the Mie-scattering and regolith scenarios, a precision of $\sim \pm3\%$ would be needed. Broadband polarimetric measurements will also need to be obtained at several phase angles to infer (or directly measure) the peak polarization.

We emphasize that the observation characteristics laid out in this section and in Table 2 are based on solar system experiences and recent studies on reflectance spectroscopy of Earth-sized rocky planets (with the exception of Damiano & Hu 2021). The figures for wavelength coverage, spectral resolution, and SNR are subject to future refinement. It is necessary to carry out studies of the reflectance spectroscopy that focuses on sub-Neptune-sized exoplanets, including and differentiating large rocky planets, water worlds, and mini-Neptunes, to optimize and pinpoint the observations needed to achieve this science case.

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