

Astro2020 APC White Paper

The Landscape for Directly Characterizing Potentially Habitable & Inhabited Planets in the Late 2020s and Beyond

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1 Key Science Goals & Objectives

The goal of this White Paper is to provide an overview of the landscape for directly characterizing potentially Earth-like planets (PEPs) at UV, optical, and near-infrared wavelengths from the late 2020s to the 2040s. We review both ground-based and space-based capabilities, noting that PEPs orbiting M dwarfs will be more easily studied from the ground (e.g., [Lopez-Morales et al., 2019](#); [Mazin et al., 2019](#); [Meyer et al., 2018](#); [Wang et al., 2019](#)) while space-based characterization is preferable for PEPs orbiting Sun-like stars. Although spectroscopic observations at mid-infrared wavelengths will also be valuable for constraining planet properties, this paper concentrates on reflected light spectroscopy and is restricted to shorter wavelengths. For more details about the path towards characterizing habitable planets at Mid-IR wavelengths, see [Staghun \(2019\)](#).

We outline our scientific goals and objectives (Section 1.1), justify the timeliness of this project (Section 1.2), and place our investigation into the broader context of exploring the formation and habitability of planetary systems (Section 1.3). In Section 2, we provide a technical overview of the various facilities that could be used to investigate planetary habitability. We then discuss the technology drivers in Section 3 and the project status, schedule, and cost estimates in Section 4.

1.1 Scientific Goals & Objectives

Is life an inevitable, common outcome of star and planet formation, surrounding us and waiting to be discovered? Or are we a cosmic fluke? Perhaps more than any other current scientific query, the search for life elsewhere touches on the very foundation of what it means to be human and can unite us in an astronomical quest for answers. This quest requires a comprehensive survey of the habitable zones of nearby stars and a search for potentially Earth-like planets (PEPs). Like any other venture in astronomy, we will require a useful sample size, large enough to study as a population. An adequate sample size of PEPs should allow us to:

- Explore the atmospheric diversity of small, temperate worlds ([Kopparapu et al., 2019](#)).
- Investigate whether inhabited planets require Sun-like host stars or whether life could exist on planets orbiting a variety of stars (e.g., [Kiang et al., 2007](#); [Schwieterman et al., 2018](#)).
- Probe the influence of stellar activity on habitability and life (e.g., [Airapetian et al., 2017](#)).
- Determine the frequency of habitable environments in the universe ([Bean et al., 2017](#)).
- Provide a reasonable chance of recognizing remotely-detectable life if it is not uncommon ([Walker et al., 2018](#)).
- Quantify how alone we are in the absence of remotely-detectable life ([Stark et al., 2014](#)).

1.2 Timeliness

Only a short time ago the risks associated with designing a direct imaging survey for PEPs were unknown. The field of planetary astronomy has matured significantly since Astro2010. For the reasons below, it is now time to pursue the search for other Earth-like worlds via direct imaging:

- Whereas a decade ago the two dominant sources of astrophysical uncertainty (the frequency of PEPs around Sun-like stars, η_{\oplus} , and the typical amount of exozodiacal dust around other stars) were largely unmeasured, we now have useful constraints on both of these quantities. We now know that Earth-sized planets are likely common in the habitable zones of Sun-like stars. We have directly measured the occurrence rates of slightly larger-than-Earth HZ planets around Sun-like stars, Earth-sized planets just interior to the HZ of Sun-like stars, and Earth-sized planets in the HZs of M-stars (e.g., [Burke et al., 2015](#); [Hsu et al., 2019](#);

Dressing & Charbonneau, 2015). Extrapolating from all three directions (radius, period, and spectral type) suggests η_{\oplus} is on the order of tens of percent. The LBTI HOSTS survey recently concluded that while a small fraction of solar-type stars have large quantities of dust, the median level is manageable, $\lesssim 4$ times the Solar System’s zodiacal dust level (Ertel et al., 2018; Mennesson et al., 2019).

- We have now quantitatively assessed the relationship between mission design and scientific yield via detailed simulations of direct imaging missions (Stark et al., 2019). Importantly, simulations have shown a surprising *insensitivity* to the dominant astrophysical sources of noise. The required aperture diameter to detect a given number of PEPs scales roughly as $\sqrt{\eta_{\oplus}}$, and the yield depends even more weakly on typical exozodi level (Stark et al., 2014).
- We are closer to understanding which planets have Earth-like bulk compositions. Our knowledge of the mass-radius-period distribution for small planets will increase considerably by the late 2020s. *TESS* is finding planets around bright stars well-suited for follow-up mass measurement and a whole slew of new RV facilities have recently started operations or will commence operations soon.
- Theoretical investigations of possible biosignatures and astrophysical false positives have advanced significantly since 2010 (Meadows, 2017; Domagal-Goldman et al., 2019; Krissansen-Totton et al., 2019; Robinson, 2019).
- We are conducting more advanced studies of star-planet interactions and the implications of stellar activity for habitability. (e.g., Garcia-Sage et al., 2017).
- The development of the technology that will enable these observations is rapidly progressing. A wide variety of coronagraph designs now exist that would work with large segmented apertures and many of the necessary performance metrics have been piece-wise demonstrated in the lab: $\sim 10^{-10}$ broadband contrasts were recently demonstrated for unobscured apertures, wavefront sensing and control (WFSC) has been demonstrated at 18% bandpass at lower contrast levels, coronagraphic masks have been manufactured and tested for the obscured WFIRST CGI aperture, and higher throughput coronagraph designs have been developed. These pieces must now be put together and demonstrated simultaneously.

1.3 Context

Directly characterizing potentially habitable planets orbiting nearby stars would revolutionize planetary astronomy and spur decades of work in observational astrobiology. Observations of PEPs around both M dwarfs and Sun-like FGK stars must be sought; the former will provide fundamental tests of planetary evolution for worlds different from the Earth-sun pairing, while the latter will offer the best chance of unambiguous life detection because false positive biosignatures may be less likely for planets around more massive stars (Arney et al., 2019). The detection and characterization of PEPs will enable the following investigations:

- Testing of basic theories of habitability, such as the influence of the carbonate-silicate cycle on the outer edge of the habitable zone (e.g., Checlair et al., 2019; Ramirez et al., 2019).
- Informing planet formation models by revealing how atmospheric composition varies with stellar type, semimajor axis, planet mass, etc. (e.g., Kopparapu et al., 2018)
- Exploring the heterogeneity of planetary atmospheres for worlds with similar host stars, orbital parameters, and bulk densities.

- Studying how planetary habitability and possibly life evolve over cosmic time by examining planets orbiting stars of different ages (e.g. [Reinhard et al., 2017](#); [Reinhard et al., 2019](#); [Krissansen-Totton et al., 2018](#)).
- Probing volatile delivery by relating the presence of volatiles to system architectures.
- Mapping rocky exoplanets, revealing the planet's continents and oceans by decomposing its time varying photometry into principle colors. (e.g., [Cowan & Agol, 2008](#))
- Searching for seasonal variations on PEPs. (e.g., [Olson et al., 2018](#))

A spectrum alone cannot provide all of the information required to fully understand a planet. Accurately interpreting habitability will require additional information:

- **Planetary Orbits:** To determine whether a planet is in the HZ, estimate the average stellar flux received, and how the instellation changes during the planet's orbit, we must measure the planet's orbit. Exoplanet orbits can be directly measured from multi-epoch direct imaging, the radial velocity method, or astrometry.
- **Planet Masses:** A planet's mass is critical to understanding its nature, and cannot be measured by direct imaging. Instead, we must rely on astrometry or radial velocity measurements of the host star (e.g. [Bendek et al., 2019](#); [Ciardi et al., 2019](#); [Dressing et al., 2019](#)).
- **Planet Radii:** To assess whether a planet is rocky, we must estimate the bulk density, which requires both mass and radius. Further, detailed modeling of an exoplanet's atmosphere requires estimates of the surface gravity. The radii of directly imaged exoplanets could be estimated loosely by established M-R relationships, directly measured from transit observations (in extremely rare cases), or constrained via direct imaging by measuring the spectrum of the planet over a broad range of wavelengths and at a broad range of phases.
- **Stellar monitoring:** Planetary habitability is set to first order by the flux it receives from its host star. Thus, obtaining roughly contemporaneous spectral energy distributions of the host star and understanding its flaring behavior are key to modeling a planet's atmosphere.

The value of directly-imaged exoplanets from future direct imaging surveys will be enhanced by synergistic investigations such as:

- Investigations that reveal infant planetary systems and protoplanets, providing constraints on when, where, and how planets form (e.g. [Monnier et al., 2019](#); [Sallum et al., 2019](#)). By statistically relating these infant systems to their mature directly-imaged counterparts, we can better understand planet migration, system evolution, and the outcome of dynamically chaotic events too short-lived to observe in the process.
- Transit observations that probe the composition of the upper levels of planetary atmospheres and refine planet radii.
- Atmospheric studies that improve models of planet formation and evolution (e.g. [Bowler et al., 2019](#); [Marley et al., 2019](#)).
- Surveys for long-period transiting exoplanets accessible to future direct imaging missions.
- Detailed characterization of potential target stars, including mass, luminosity, binarity, activity, and abundances (e.g. [Airapetian et al., 2019](#); [Hinkel et al., 2019a,b](#)).
- Simulated blind planet retrieval studies (e.g., the WFIRST CGI SIT data challenge)

2 Technical Overview

A variety of facilities have been planned, designed, or proposed to directly characterize PEPs. Below, we provide a brief overview of a subset of these facilities. For additional information, we encourage readers to consult the linked white papers and web pages.

2.1 JWST (*Mission Website*)

Mission Overview: A 6.5-m telescope with four instruments planned for launch in March 2021 on an Ariane 5 rocket. Direct imaging of exoplanets will be possible with the Near-Infrared Camera (NIRCam), the Mid-Infrared Instrument (MIRI), and the Near InfraRed Imager and Slitless Spectrograph (NIRISS). JWST also includes a Near-Infrared Spectrograph (NIRSpec).

Performance: As discussed by [Beichman et al. \(2019\)](#), NIRCam coronagraphy will be possible up to Inner Working Angles (IWA) of $4\lambda/D$, which translates to a separation of $0.4''$ at $3.0\mu\text{m}$ and $0.6''$ at $4.4\mu\text{m}$. For MIRI, Four Quadrant Phase Masks can be employed to reach an effective IWA of λ/D , which corresponds to $0.4''$ at $11.4\mu\text{m}$. At separations of $1''$, NIRCam and MIRI are expected to reach contrasts of 10^{-5} and 10^{-4} , respectively ([Perrin et al., 2018](#); [Beichman et al., 2010](#); [Krist et al., 2007](#); [Boccaletti et al., 2015](#); [Danielski et al., 2018](#)). The Aperture Masking Interferometer (AMI) mode of NIRISS will be ideal for reaching even smaller IWA of $0.5\lambda/D$, thereby probing down to separations of $0.08''$ for observations at $3 - 5\mu\text{m}$. NIRISS AMI is expected to achieve contrasts of $10^{-3} - 10^{-4}$ ([Artigau et al., 2014](#)).

For exoplanet imaging, JWST's strengths are the ability to achieve higher sensitivities than current ground-based facilities for observations at redder wavelengths ($\lambda > 3\mu\text{m}$) and, for NIRCam and MIRI, the ability to image planets at separations that would be beyond the Outer Working Angle (OWA) of ground-based facilities. JWST is expected to constrain theoretical models of planetary evolution by detecting Saturn-mass and Neptune-mass planets around young stars, while past ground-based surveys have been limited to planets significantly more massive than Jupiter ($M_p > 5M_J$). JWST will both re-observe previously known planetary systems (e.g., HR 8799, 51 Eri, HD 95086) and conduct new searches for Jupiter-mass planets at $2'' - 10''$ separation from young stars with previously detected debris disks and self-luminous exoplanets. For M dwarfs, JWST will probe down to smaller planet masses ($M_p \sim M_{Uranus}$) and separations of 10-20 AU ([Schlieder et al., 2015](#)). In addition, the AMI mode of NIRISS will be used to search for infant planets (< 10 Myr, $M_p \gtrsim 1M_J$) in star forming regions.

For planet characterization, multi-band photometry with NIRCam and MIRI will probe the composition of exoplanet atmospheres by detecting or placing upper limits on the presence of molecules like CH_4 , CO , CO_2 , and NH_3 . These observations will also inform planet formation models (e.g., [Marley et al., 2007](#); [Spiegel & Burrows, 2012](#)) by constraining planet luminosities, effective temperatures, and radii. Spectroscopically, observations with NIRSpec (using slits or the $R \sim 1000$ IFS) and MIRI (using the $R \sim 100$ Low Resolution Spectrometer or the $R \sim 2500$ Medium Resolution Spectrometer) will provide a rich dataset of direct spectra of young gas giants. PEPs and other planets smaller than Uranus or inside 5-10 AU will be out of reach.

2.2 WFIRST (*Mission Website*)

Mission Overview: A 2.4-m telescope with an obscured pupil and two instruments: a wide-field imager (WFI) and a coronagraph (CGI). The CGI is a technology demonstration instrument intended to advance high-performance, space-based direct imaging of exoplanets. The CGI will demonstrate in space, for the first time, high-contrast coronagraphy using active deformable mirrors and a closed loop wavefront sensing and control system. Currently, the CGI intends to fly

a low-resolution ($R=50$) integral field spectrograph. An external starshade to rendezvous with WFIRST and use the CGI as a back-end science instrument has been studied as a separate Probe-scale mission (S. Seager, APC White Paper).

Performance: The CGI has a contrast requirement of a few $\times 10^{-8}$, such that it can image some currently known, warm young giant exoplanets in thermal emission in the optical and perform spectroscopy of a few. The predicted CGI contrast is somewhat better (few $\times 10^{-9}$) which would permit detection of a few known radial velocity planets in reflected light. In either case, direct observations of terrestrial planets with CGI will be out of reach. Observations of potentially Earth-like planets around a handful of the very nearest stars using a starshade may be possible.

2.3 *Exo-C (Mission Concept Website)*

Mission Overview: Exo-C is a probe-class mission concept optimized for coronagraphic imaging of planetary systems (K. Stapelfeldt, APC White Paper). The outcome of a detailed mission study, Exo-C would be capable of spectrally characterizing 1-2 dozen nearby giant exoplanets in reflected visible light to measure atmospheric composition, discover previously undetected planets, and image structure in hundreds of circumstellar disks. It would obtain unique science results on planets down to super-Earth size and serve as a technology pathfinder toward an eventual flagship-class mission to find and characterize habitable Earth-like exoplanets. Exo-C's telescope aperture, orbit, mission lifetime, and spacecraft bus are all comparable to the Kepler telescope. An unobscured telescope aperture and deformable mirrors for wavefront control would feed two instruments, an imaging camera and an integral field spectrometer.

Performance: The coronagraph would produce a 10^{-9} raw contrast dark field at radii of $2-20 \lambda/D$ from the star. The imager fully covers this field with filters over the wavelength range 450 – 1000 nm. A smaller field 1.2" in radius is covered by the IFS ($R = 70$, 450 – 1000 nm). Among selected nearby stars this capability would permit detection of Jupiter-like planets with semi-major axes out to 9 AU, Neptune-like planets out to 3 AU and super-Earths out to 1 AU. Under the most favorable telescope stability and exo-zodi conditions Earth-twins might be detected around a few of the nearest stars. Spectral characterization of the brightest planet discoveries—from exo-Jupiters to any nearby Earths—will be obtained. For giant planets, atmospheric characterization would include photochemical haze and cloud properties and the abundance of key molecular absorbers, including H_2O and CH_4 and, for warmer planets, Na and K.

2.4 *Exo-S (Mission Concept Website)*

Mission Overview: A probe-class exoplanet direct imaging mission concept that uses an external starshade to suppress light from the planet host star. In the Rendezvous Mission Concept, the starshade would work with an existing 2.4-m telescope at L2 (S. Seager, APC White Paper; discussed in Section 2.5). In the Dedicated Mission Concept, a 30-m starshade would be launched with a small (1.1-m) telescope dedicated to Exo-S. The telescope would have three instrument packages: (1) a planet camera with a 1' FOV, (2) an integral field spectrograph with a 3" FOV, (3) a fine guidance camera with a 2' FOV for navigation and formation flying with the starshade. Exo-S will be capable of direct imaging, polarization measurements, and spectroscopy at resolutions up to $R=70$ between 400 nm and 1000 nm.

Performance: The Dedicated Mission has a contrast requirement of a 4×10^{-11} . Exo-S will discover new exoplanets around the nearest stars, obtain spectra of both newly discovered and previously known planets (largely newly detected sub-Neptunes and previously detected giant plan-

ets), and observe planetary systems to study connections between planets and circumstellar dust. The mission concept could discover PEPs in the habitable zones of at least 10 Sun-like stars using broad-band imaging, integrating the planet light across the full bandpass to increase the SNR. For most PEPs, spectroscopic follow-up would require unrealistically long integration times. The Dedicated Mission will therefore acquire 3-band photometry so that planets can be roughly classified using colors. For the most favorable PEPs, the Dedicated Mission could obtain low-resolution ($R=10$) spectra at $\text{SNR}=10$.

2.5 *Starshade Rendezvous (Final Report)*

Mission Overview: A probe-class mission concept to launch a 26-m starshade to rendezvous with the 2.4-m WFIRST telescope (see Section 2.2). The mission objectives are: (1a) search the habitable zones of nearby stars for small planets and look for biosignatures, (1b) detect other types of planets orbiting nearby stars, (2) investigate the brightness of zodiacal dust disks surrounding nearby stars, and (3) determine the atmospheric metallicity of known, cool giant planets.

Performance: The mission could directly image PEPs orbiting nearby Sun-like stars and will intensely observe the nearest 10-12 Sun-like stars. Adopting an occurrence rate of $\eta_{\oplus} = 0.24$ from the ExoPAG SAG-13 report (Belikov et al., 2017), Starshade Rendezvous is anticipated to detect roughly 1.3 PEPs. For 0.4 PEPs, Starshade Rendezvous will be able to verify that the planet orbits in the habitable zone and obtain $\text{SNR} > 20$ spectra for planet characterization. The mission is also predicted to discover roughly 8 additional non-habitable planets orbiting the nearest Sun-like stars, measure the level of exozodiacal dust around 10 stars, and obtain $\text{SNR} > 15$ spectra to measure the atmospheric metallicities of roughly 10 giant planets and investigate trends between planet metallicity, mass, and orbital parameters.

2.6 *HabEx (Mission Concept Website)*

Mission Overview: A Large Strategic Mission Concept studied for the 2020 Astrophysics Decadal Survey. As described in the APC White Paper by Gaudi et al. (2019), the HabEx team has considered nine possible mission concepts, each of which is optimized for exoplanet detection and characterization while enabling a broad range of non-exoplanet science. Together, the mission concepts consider a broad range of possible configurations including three different starlight suppression technologies (starshade, coronagraph, or both) and three different sizes of the primary mirror (2.4-m, 3.2-m, and 4-m). Below, we discuss the anticipated performance of the preferred concept: a 4-m monolithic, off-axis telescope that is diffraction-limited at $0.4\mu\text{m}$ and includes both a vector vortex coronagraph and a 52-m starshade that will fly 76,600 km from the telescope. Including both a coronagraph and a starshade allows HabEx to take advantage of the strengths of both techniques by conducting initial planet searches using the coronagraph and switching to the starshade for characterization or deeper surveys.

Performance: When used in coronagraphic mode, HabEx can detect planets as close as the 62 mas inner working angle of the coronagraph. For the nominal starshade separation of 76,600 km, HabEx will be sensitive to planets between a tighter inner working angle of $\text{IWA}=58$ mas and a wide outer working angle of $\text{OWA}=6''$. The starshade also enables simultaneous spectroscopy over a broad wavelength range from $0.3\mu\text{m}$ to $1\mu\text{m}$ at the default separation. Observations at bluer wavelengths of $0.2\text{--}0.67\mu\text{m}$ and redder wavelengths of $0.54\text{--}1.8\mu\text{m}$ can be obtained by increasing and decreasing the distance between the starshade and the telescope. The spectral resolution is set to $R = 7$ between $0.2\mu\text{m}$ and $0.45\mu\text{m}$, $R = 140$ between $0.45\mu\text{m}$ and $1\mu\text{m}$, and $R = 40$ at longer

wavelengths. The vast majority of planets detected by the coronagraph – and all PEPs - will have spectra measured by the starshade over a region covering at least 0.3 to 1 μm .

Roughly 50% of the 5-year prime mission will be spent conducting two complementary exoplanet surveys: (1) a deep survey of the eight nearest Sun-like stars and (2) a broad survey of 42 nearby stars. For the deep survey, HabEx will be sensitive to planets as small as Mars (final contrast = 2.5×10^{-11}). The broad survey is slightly shallower and is optimized for PEPs among many nearby stars. HabEx is expected to detect more than 150 diverse exoplanets in total, including approximately 37 rocky planets near the habitable zone and roughly 8 PEPs during these surveys. For PEPs, HabEx will determine orbits and obtain spectra from 300 nm to 1000 nm to search for Rayleigh scattering and molecular features (e.g., H_2O , O_2 , O_3), with $R=140$ and $\text{SNR}=10$ at visible wavelengths. For the most promising systems, HabEx will extend its spectral coverage from 200 nm to 1800 nm and search for specular reflection from surface liquid water oceans.

2.7 LUVOIR (*Mission Concept Website*)

Mission Overview: A Large Strategic Mission Concept studied for the 2020 Astrophysics Decadal Survey. As described in the APC WP by [Roberge & the LUVOIR STDT \(2019\)](#), the LUVOIR Team considered both a 15-m, on-axis telescope (LUVOIR-A) and an 8-m, off-axis telescope (LUVOIR-B). Both observatories would be located at Sun-Earth L2 and offer broad wavelength coverage (100 - 2500 nm), a large instantaneous field-of-regard, the ability to track moving targets, and an exquisitely sensitive instrument suite including ECLIPS, an ultra-high contrast coronagraph with imaging cameras and integral field spectrographs.

Performance: ECLIPS will feature three simultaneously-operable channels: NUV (200-525 nm), visible (515-1030 nm), and NIR (1000-2000 nm). Multi-band ($\sim 10 - 20\%$) imaging will be possible in the NUV and visible channels, while integral field spectroscopy will be possible in the visible and NIR. The optical IFS has a resolution of $R=140$, which was selected to probe the narrow O_2 absorption band at 760 nm. The NIR channel includes a lower resolution IFS ($R=70$) to capture broad molecular absorption bands and a single planet spectrograph with $R=200$ for detection of CO_2 . For both LUVOIR-A and LUVOIR-B, all of the selected coronagraph masks are designed to reach contrasts $\sim 10^{-10}$ in the dark zone to search for and characterize PEPs.

LUVOIR-A's version of ECLIPS (ECLIPS-A) features an Apodized Pupil Lyot Coronagraph (APLC) as the primary coronagraph. Using the APLC, ECLIPS-A will search for planets between $\text{IWA}=3.7\lambda/D$ and $\text{OWA}=64\lambda/D$ (51-440 mas for 0.5 – 1.0 μm coverage). Maintaining 10^{-10} contrast is a challenge for some coronagraph designs with an on-axis telescope like LUVOIR-A, as the stellar diameters are quasi-resolved. The APLC achieves 10^{-10} contrast even for the largest, nearest stars in our target list. A few tens of nearby M stars are bright, but have very compact HZs inaccessible to the APLC. For these stars, stellar radius is not a concern, and ECLIPS-A uses an Apodized Vortex Coronagraph (AVC) with an aggressive IWA to characterize these planets at the red end of the spectrum.

The off-axis design of LUVOIR-B removes the central obscuration, so a wider variety of coronagraph designs exist that are robust to stellar diameter. For ECLIPS-B, the primary coronagraph is a charge 6 Deformable Mirror-assisted Vortex Coronagraph (DMVC) with an $\text{IWA}=3.8\lambda/D$ (useful throughput/suppression down to $\sim 2.5\lambda/D$) and an $\text{OWA}=64\lambda/D$. Compared to the ECLIPS-A APLC, the ECLIPS-B DMVC exhibits a factor of two increase in both core throughput and instantaneous bandwidth.

LUVOIR will be sensitive to Earth-size planets in the habitable zones of nearby stars. During a

two-year survey optimized for PEPs around nearby AFGKM stars (roughly 290 for LUVOIR-A and 160 for LUVOIR-B), LUVOIR-A is expected to detect 54^{+61}_{-34} habitable candidates and LUVOIR-B is predicted to detect 28^{+30}_{-17} . These sample sizes of habitable planet candidates are large enough to provide a good shot at finding at least one *truly habitable* planet; LUVOIR-B would detect at least one habitable planet with 95% confidence, even if only 10% of all candidates in the universe actually are habitable, and LUVOIR-A could detect at least one even if only 5% are habitable. If the occurrence rate of habitable environments is higher, then both facilities should detect multiple habitable planets, thereby enabling statistical investigations of planetary habitability like those discussed in [Checlair et al. \(2019\)](#). These sample sizes are also large enough to place meaningful constraints on the occurrence rate of habitable environments *even if no habitable planets are found*; in the event of no signs of habitability, LUVOIR-B could constrain the rate of habitable environments existing on rocky HZ planets to $< 10\%$ and LUVOIR-A could constrain it to $< 5\%$ with 95% confidence.

While searching for PEPs, both observatories will serendipitously observe hundreds of non-habitable planets (≈ 648 for LUVOIR-A and ≈ 576 for LUVOIR-B). For initial screening of PEPs, LUVOIR will acquire $R = 70$ spectra at $SNR > 5$ to search for H_2O at $0.94\mu m$. If candidates display signs of water, then LUVOIR will obtain additional visible spectra ($R=140$, $SNR \sim 10$) and NIR spectra ($R=70$, $SNR \sim 10$) to better constrain water abundance and search for additional biosignatures such as O_2 , O_3 , and CH_4 ([Feng et al., 2018](#)). In parallel, UV observations (with LUVOIR or other facilities) will be used to characterize the host star and investigate how stellar activity might affect atmospheric photochemistry and erosion (e.g. [Christiansen et al., 2019](#); [Lopez et al., 2019](#)). For M dwarf planets in particular, UV observations are essential for correctly interpreting biosignatures and identifying false positives caused by stellar activity (e.g. [Meadows, 2017](#)). The majority of PEPs detected by LUVOIR will orbit Sun-like stars and therefore be less likely to exhibit oxygen false positives (e.g. [Tian et al., 2014](#); [Arney et al., 2019](#)).

Assessing habitability also requires knowledge of planetary orbits and masses. The High-Definition Imager (HDI) provides the ability to measure planet masses directly with LUVOIR via high precision astrometry. For each target, 14 epochs of observation are required for LUVOIR-A or 40 epochs with LUVOIR-B. The total observing time needed to measure the masses of all exoEarth candidates is 30 days for the 54 candidates detected by LUVOIR-A and 40.5 days for the 28 candidates detected by LUVOIR-B. In both cases, the time estimates are dominated by overhead. Planet masses could also be measured using radial velocity or astrometric observations from other facilities.

2.8 OST (*Mission Concept Website*)

Mission Overview: A Large Strategic Mission Concept studied for the 2020 Astrophysics Decadal Survey. The Origins Concept-2 baseline design features a 5.9-m telescope actively cooled to 4.5K and diffraction-limited at $30\mu m$. The observatory includes three science instruments: the Mid-Infrared Spectrometer (MISC, $\lambda = 2.8 - 20\mu m$), the Origins Survey Spectrometer (OSS, $\lambda = 25 - 590\mu m$, $R=300$, $R=43,000$, or $R=325,000$), and the Far-Infrared Imager and Polarimeter (FIP; $50\mu m$ and $250\mu m$).

Performance: For exoplanet science, OST will primarily concentrate on transit and emission spectroscopy with the MISC instrument. For the small fraction of PEPs orbiting late M dwarfs that happen to transit, these observations could reveal the presence of potential biosignatures, including O_3 , N_2O , and CH_4 . It could also detect the presence of greenhouse gases, including H_2O , O_2 , CO_2 ,

and CH₄. Combined with its capability to constrain temperature-pressure profiles, this could lead to a relatively detailed understanding of the climates of individual PEP’s around late M-type stars (Fortney et al., 2018).

2.9 ELT (*Observatory Website*)

Observatory Overview: A segmented, ground-based 39-m telescope that will feature a high-resolution spectrograph (HIRES), a Mid-infrared ELT Imager and Spectrograph (METIS), a Multi-object spectrograph (MOSAIC), a Multi-AO Imaging Camera for Deep Observations (MICADO), a High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI), and a Multi-conjugate Adaptive Optics Relay for the ELT (MAORY).

Performance: The mid-infrared imager and spectrograph (METIS) will provide imaging, coronagraphy, and spectroscopy in the L , M , and N bands. Medium-resolution spectroscopy will be possible between $3\mu\text{m}$ and $19\mu\text{m}$ and higher resolution integral field spectroscopy ($R \sim 100,000$) will be available between $3\mu\text{m}$ and $5\mu\text{m}$.

2.10 GMT (*Observatory Website*)

Observatory Overview: A segmented, ground-based telescope comprised of six off-axis 8.4-m monolithic segments surrounding a central on-axis segment. GMagAO-X is a concept for an “extreme” adaptive optics system capable of producing high-Strehl, high-contrast images at visible wavelengths (Males et al., 2019). GMagAO-X would include seven 3000-actuator MEM deformable mirrors (one for each segment of the primary mirror).

Performance: GMagAO-X aims to observe some of the currently known exoplanets detected by RV surveys in reflected light. The sample of possible targets includes $1 - 12R_{\oplus}$ planets orbiting stars with a broad range of spectral types from mid-M dwarfs to Sun-like stars. For nearby stars, GMagAO-X could be sensitive to PEPs.

2.11 TMT (*Observatory Website*)

Observatory Overview: A segmented, ground-based, folded Ritchey-Chrétien telescope with an aperture of 30 meters. MODHIS (Multi-Object Diffraction-limited High-resolution Infrared Spectrograph) is targeted as a first-light instrument for TMT, and designed to be fed by NFIRAOS (and PSI, see below), the first-light AO system for TMT. MODHIS will take $R > 100,000$ spectra of a few objects in a $10''$ field-of-view sampled at the diffraction limit (10 mas scale), simultaneously from 0.95 to $2.4\mu\text{m}$ (y band to K band). When fed with NFIRAOS, MODHIS also includes modest high-contrast capabilities enabling the discovery of young giant planets at short separation and the characterization of faint off-axis objects such as directly imaged exoplanets. Being fiber fed, the MODHIS spectrograph can also be fed by subsequent extreme AO facilities such as the Planetary Systems Imager (PSI, Fitzgerald et al., 2019).

PSI is prioritized by the TMT Science Advisory Committee for the second generation of instruments and supports imaging ($\lambda = 0.6 - 5.3\mu\text{m}$), polarimetry ($\lambda = 0.6 - 5.3\mu\text{m}$), integral field spectroscopy ($R=50$ at $\lambda = 0.6 - 5.3\mu\text{m}$, $R \sim 30$ at $\lambda = 8 - 13\mu\text{m}$, and $R=5000$ at $\lambda = 2 - 5.3\mu\text{m}$), and high-resolution spectroscopy with MODHIS ($R=100,000$, $\lambda = 0.6 - 5.3\mu\text{m}$). PSI will also include a thermal channel at $10\mu\text{m}$. PSI will detect and characterize rocky planets, ice giants, and gas giants around nearby stars. The giant planet sample will include both mature giants and young, massive self-luminous planets.

Performance: For resolved observations close to the diffraction limit λ/D between $0.95\mu\text{m}$ and $2.4\mu\text{m}$, MODHIS will achieve a raw contrast of 10^{-3} with NFIRAOS at first light. The final con-

trast achieved by MODHIS will depend on the potential gain provided by the cross-correlation high-resolution template matching technique. The technique has demonstrated 10^{-4} contrast gains in combined light yielding a possible 10^{-7} final contrast in favorable configurations (Snellen et al., 2015), enabling the detection of the thermal emission of young giant planets at very short separations (AU scale), as well as reflected light from ice giants and down to sub-Neptunes.

For observations at $1-2\lambda/D$ between $0.6\mu\text{m}$ and $1.8\mu\text{m}$, PSI is designed to achieve a raw contrast of 10^{-5} and a final contrast of 10^{-8} . For the close stars, PSI will be sensitive to sub-Neptunes and for the closest M dwarfs, PSI could detect reflected starlight from PEPs as well as ice and gas giants. The habitable zones of M dwarfs are extremely close to their host stars, but the small IWA of PSI is well-suited to the challenge. For the most nearby Sun-like stars, observations at $8-13\mu\text{m}$ may reveal thermal emission from PEPs (Quanz et al., 2015). In the low-resolution integral field spectroscopy mode, long-wavelength observations could reveal biosignatures such as H_2O , CH_4 , O_3 , and CO_2 . At shorter wavelengths of $3-5\mu\text{m}$, warm (400-600 K) rocky planets orbiting the closest FGK stars could be detected in thermal emission (Crossfield, 2013). For a handful of planets orbiting extremely nearby stars, PSI will be able to detect planets in both reflected light and thermal emission, enabling novel investigations of the energy budget and climate of other worlds.

3 Technology Drivers

The required technology and notional development path for each concept is addressed in detail in the associated white papers. Please see the corresponding links for each study as well as related white papers (Belikov et al., 2019; Currie et al., 2019; Crill et al., 2019b,a; Mazoyer et al., 2019; Shaklan, 2019) and the analysis of effects and mitigation of polarization aberrations on high-contrast imaging system performance by Will & Fienup (2019). For alternative telescope designs, see Monreal et al. (2019).

4 Project Status, Schedule, & Cost Estimates

The current status, schedule, and cost estimate for each project is listed in Table 1. For detailed information for each facility, see the associated white papers.

Table 1: Status & Cost Estimates of Related Projects

Facility	Status	WP Reference
JWST	scheduled to launch in 2021	—
WFIRST	in formulation in Phase B	—
Exo-C	study completed; final report at link	Stapelfeldt et al.
Exo-S	study completed; final report at link	Seager et al.
Starshade Rendezvous	probe concept study nearing completion; report at link	Seager et al.
LUVOIR	large mission concept study nearing completion	Roberge et al.
HabEx	large mission concept study nearing completion	Gaudi et al.
OST	large mission concept study nearing completion	Leisawitz et al.
ELT	first-light scheduled for 2024	—
GMT	first-light scheduled for 2025	Males et al.
TMT	first-light scheduled for 2026	Fitzgerald et al.

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