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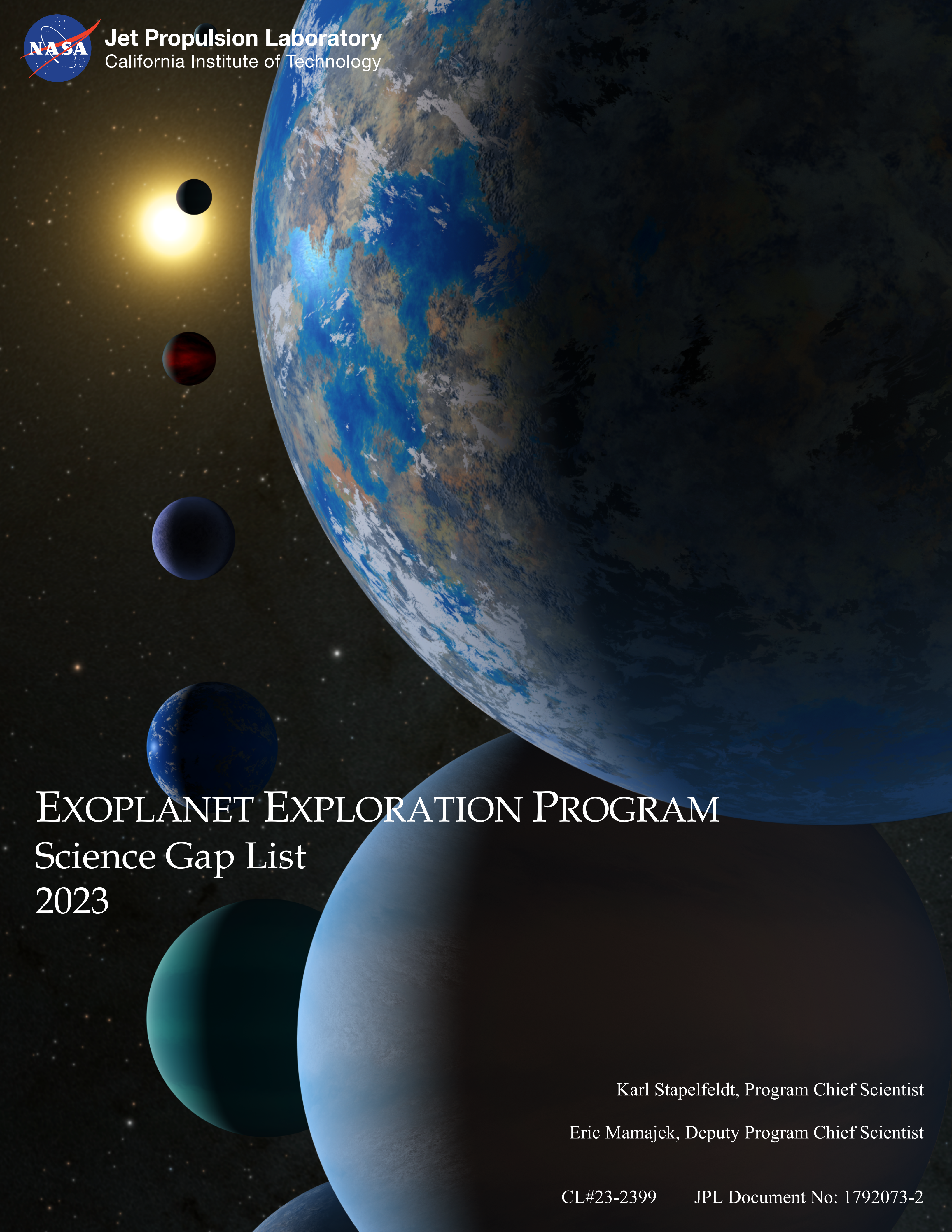

EXOPLANET EXPLORATION PROGRAM
Science Gap List
2023

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Cover Art Credit: NASA/JPL-Caltech. Artist conception of the variety of different types of exoplanets, with a potentially habitable world similar to Earth in the foreground. The artwork accompanied the NASA press release “*Cosmic Milestone: NASA Confirms 5,000 Exoplanets*” published on March 21, 2022 written by Pat Brennan. The original caption reads “*What do planets outside our solar system, or exoplanets, look like? A variety of possibilities are shown in this illustration. Scientists discovered the first exoplanets in the 1990s. As of 2022, the tally stands at just over 5,000 confirmed exoplanets*.”

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1. Introduction to the 2023 Exoplanet Exploration Program (ExEP) Science Gap List

The Exoplanet Exploration Program (ExEP) is chartered by the Astrophysics Division (APD) of NASA's Science Mission Directorate (SMD) to carry out science, research, and technology tasks that advance NASA's science goals for exoplanets, which are:

- *Discover planets around other stars,*
- *Characterize their properties, and*
- *Identify candidates that could harbor life*

ExEP serves NASA and the community by acting as a focal point for exoplanet science and technology, managing research and technology initiatives, facilitating access to scientific data, and integrating the results of previous and current missions into a cohesive strategy to enable future discoveries. ExEP serves the critical function of developing the concepts and technologies for exoplanet missions, in addition to facilitating science investigations derived from those missions. ExEP manages development of mission concepts, including key technologies, as directed by NASA HQ, from their early conceptual phases into pre-Phase A.

The goal of the *ExEP Science Plan* is to show how the Agency can focus its science efforts on the work most needed to realize the goal of finding and characterizing habitable exoplanets, within the context of community priorities. The *ExEP Science Plan* consists of three documents, which will be updated periodically, which respond directly to the ExEP Program Plan:

- ExEP Science Development Plan (SDP)
- ExEP Science Gap List (SGL) (this document)
- ExEP Science Plan Appendix (SPA)

The long-term online home of the science plan documents is:
https://exoplanets.nasa.gov/exep/science-overview/.

The ExEP *Science Development Plan* (SDP) reviews the Program's objectives, the role of scientific investigations in ExEP, important documentation, and the programmatic framework for ExEP science.

This document, the ExEP *Science Gap List* (SGL), tabulates program "science gaps", which are defined as either:

- *The difference between knowledge needed to define requirements for specified future NASA exoplanet missions and the current state of the art, or*

- *Knowledge which is needed to enhance the exoplanet science return of current and future NASA exoplanet missions.*

Making the gap list public signals to the broader community where focused activities and investigations are needed over the next 3-5 years to advance the goals of NASA's Exoplanet Exploration Program. All ExEP approaches, activities, and decisions are guided by science priorities, and those priorities are presented and summarized in the ExEP Science Gap List.

The *Science Plan Appendix* (SPA) lays out the scientific challenges that must be addressed to advance the goals of NASA's Exoplanet Exploration Program. While the Program Science Development Plan is expected to remain stable over many years, the Science Gap List will be updated annually, and this Science Plan Appendix will be updated approximately every five years, or as needed. Entries in the *Science Gap List* will map to sections of the *Science Plan Appendix*.

The central community report relevant to the NASA ExEP is the *Pathways to Discovery in Astronomy and Astrophysics for the 2020s* (*Astro2020*) Decadal survey report from the National Academies of Sciences, Engineering, and Medicine released in November 2021. *Astro2020* included input from two other recent National Academies reports: the National Academies' *Exoplanet Science Strategy* (ESS) and *An Astrobiology Strategy for the Search for Life in the Universe*, both released in late 2018. *Pathways to Discovery in Astronomy and Astrophysics for the 2020s* identifies the most compelling science goals and presents an ambitious program of ground- and space-based activities to address them through investments in the 2020s and beyond. *Astro2020* identifies three major science themes for the next decade, the first of which (*Worlds and Suns in Context*) calls for investigations of Earth-like exoplanets. Two other themes focus on the most energetic processes in the universe and the evolution of galaxies.

The *Exoplanet Science Strategy* report provided a broad-based community assessment of the state of the field of exoplanet science and recommendations for future investments. NASA HQ's major response to the ESS report was to charter the "Extreme Precision Radial Velocity Working Group" (EPRV-WG), which developed and presented a blueprint for a strategic EPRV initiative to NASA and NSF in March 2020, and produced a final report in summer 2021[1].

The 2018 Exoplanet Science Strategy report provided seven recommendations, thirty-five findings, and two "*overarching goals in exoplanet science*":

- *to understand the formation and evolution of planetary systems as products of the process of star formation, and characterize and explain the diversity of planetary system architectures, planetary compositions, and planetary environments produced by these processes, and*

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[1] Extreme Precision Radial Velocity Working Group (EPRV WG) Final Report, May 2021: https://exoplanets.nasa.gov/internal_resources/2000/ and https://arxiv.org/abs/2107.14291

- *to learn enough about the properties of exoplanets to identify potentially habitable environments and their frequency, and connect these environments to the planetary systems in which they reside. Furthermore, scientists need to distinguish between the signatures of life and those of nonbiological processes, and search for signatures of life on worlds orbiting other stars*

The recommendations from Astro2020, the 2018 *Exoplanet Science Strategy* and the 2018 *An Astrobiology Strategy for the Search for Life in the Universe* reports are all factored into the *2023 ExEP Science Gap List*. The "*highest priority for space frontier missions*" is a future large near-infrared/optical/ultraviolet space telescope optimized for observing habitable exoplanets and general astrophysics, nominally with diameter ~6 meters and capable of high-contrast ($\sim 10^{-10}$) imaging and spectroscopy, and which we now refer to as the *Habitable Worlds Observatory.* The *Astro2020* recommendation aligned well with the 2018 ESS recommendation that NASA lead "*a large strategic direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars,"*

The *Astro2020* Decadal Survey science theme *Worlds and Suns in Context* had two science panel discovery areas ("The Search for Life on Exoplanets" and "Detecting and Characterizing Forming Planets") and several questions from the Decadal Science Panels (Table 2.1 of Astro2020) which map to gaps in the ExEP Science Gap List:

- E-Q1: What is the range of planetary system architectures, and is the configuration of the solar system common?
- E-Q2: What are the properties of individual planets, and which processes lead to planetary diversity?
- E-Q3: How do habitable environments arise and evolve within the context of their planetary systems?
- E-Q4: How can signs of life be identified and interpreted in the context of their planetary environments?
- F-Q4: Is planet formation fast or slow?
- G-Q3: What would stars look like if we view them like we do the Sun?

The 2023 SGL notes the linkage between each ExEP Science Gap and these *Astro2020* science questions.

In April 2022 the National Academies released a second Decadal Survey *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032*. While it makes no recommendations for exoplanet missions or projects, its Chapter 12 provides an extensive list of exoplanet science questions and identifies areas for strategic research, anchored to the overall question "*What does our planetary system and its circumplanetary systems of satellites and rings reveal about other planetary systems, and what can disks and exoplanets orbiting other stars teach us about the solar system?*" We have noted connections between ExEP Science Gaps and these questions where appropriate.

The ExEP science gaps do *not* appear in a particular order, and by being recognized on this list are deemed important. Currently the gap list is used when evaluating possible new Program activities: if a proposed activity could close a gap, it would be considered for greater priority for Program resources. The ExEP Science Gap List is *not* meant to provide strategic community guidance on par with a National Academies report (e.g., Decadal Surveys, Exoplanet Science Strategy, etc.), but to provide program-level tactical guidance for program management within the ever-shifting landscape of NASA missions and mission studies. Funding sources outside NASA ExEP are free to make their own judgments as to whether or not to align the work they support with NASA's Exoplanet Exploration goals. Science gaps directly related to specific missions in phase A-E are relegated to those missions and are not tracked in the ExEP SGL. However, science gaps that facilitate science investigations derived from those missions, or support phase A or pre-phase A studies of new missions, may appear in the SGL.

Following usage in the two NASA Precursor Science Workshops ("Precursors to Pathways: Science Enabling NASA Astrophysics Future Great Observatories") held in April and October 2022, we adopt these definitions to clarify the nature of science investigations, their relevance to NASA missions, and their urgency:

- **Precursor Science:** Informs mission design, architecture, and trades.
    - When needed: Now.
    - Example: Astro 2010 Decadal Survey pointed out "*measurement of exozodiacal light levels*" that would "*determine the size and complexity*" capable of imaging rocky planets orbiting within the habitable zones of nearby stars.

- **Preparatory Science:** Informs early operations or interpretation of data.
    - When needed: By or after launch.

- **Follow up Science:** Investigations that follow up on discoveries or other science from the mission.
    - When needed: After launch, but potentially coordination and planning is required prior to launch.

Section 3 provides a list of the acronyms commonly used by NASA ExEP which may be encountered among the SGL descriptions.

Section 4 discusses some adopted definitions for a few exoplanet terms.

Note: This updated version (Revision G; dated June 20, 2023) fixes some typos present in the 2023 ExEP Science Gap List document dated May 16, 2023 (Revision F).

2. The 2023 Exoplanet Exploration Program (ExEP) Science Gap List

2.1. SCI-01: Spectroscopic observations of the atmospheres of small exoplanets

- For context see SPA Section 6 (atmospheres & biosignatures)
- Connects to Astro2020 Decadal Science Panel Questions E-Q1, E-Q2, E-Q3, E-Q4
- Connects to PSA2022 Decadal Science Questions 12.3, 12.6, 12.10, 12.11
- *Related gaps:* limits to precision on extracting spectra (gap SCI-03), need for accurate ephemerides for scheduling transit spectroscopy observations (gap SCI-09), value of precursor surveys to find direct imaging targets (gap SCI-10).

Gap Summary:
The study of planetary atmospheres advances our knowledge of planetary formation and evolution. The Large Near-IR/Optical/UV space telescope recommended by Astro2020 (HWO) will image and spectrally characterize, in the UV/vis/near-IR regime a robust sample of ~25 potentially habitable exoplanets. There are few extant spectroscopic detections of atmospheres for exoplanets smaller than Neptune, even though they dominate the known exoplanet population. While some spectral constraints have been obtained for sub-Neptunes and super-Earths, detection of spectral features for temperate Earth-sized exoplanets has been beyond current capabilities. To remotely assess the frequency of habitable planets and life, new observations and facilities must be developed to characterize the atmospheres of small exoplanets. Spectroscopic observations of small exoplanets by JWST and HST could provide preparatory science to enhance the science return for Roman coronagraph and ARIEL/CASE, and could provide precursor science observations to influence the design of HWO.

Capability Needed:
Spectroscopy of small exoplanets across a diverse range of planet sizes and compositions, stellar types, and radiation environments e.g., transit spectroscopy of small planets transiting cool dwarf stars, and high-contrast spectroscopy of small exoplanets orbiting solar-type (FGK-type) stars. Temperate examples are of particular interest for searching for biosignatures. Targets are needed that provide the most photons (i.e., orbiting nearby, brightest stars for their class).

Capability Today:

- A handful of small exoplanets identified by RV and transit surveys have been pursued with spectroscopic followup. HST and ground-based transit spectra have provided the first constraints for these sub-Neptune sized planets but have marginal sensitivity only sufficient to detect spectral features in cloud-free H-dominated atmospheres.
- To date TESS has identified ~130 small, mostly hot exoplanets suitable for spectroscopic followup.
- Launched in 2021, JWST is now performing precise spectroscopic followup of exoplanets.
- So far there are no imaging detections of small exoplanets.

- The LUVOIR and HabEx mission concept studies provided input on the capabilities needed for studying the atmospheres of small exoplanets via reflected light direct imaging - relevant for HWO.

Mitigations in Progress:

- There are approved JWST Cycle 1 observations to spectrally characterize more than 30 small (sub-Neptune or smaller) transiting exoplanets, many of which were discovered by TESS.
- High dispersion spectroscopy coupled with extreme AO coronagraphy is being developed at ESO and Keck and may provide some detections of hot planets smaller than Neptune, if their velocity amplitudes are large enough to distinguish their spectral lines from stellar and telluric features.
- The Pandora smallsat will observe about a dozen small exoplanets for transit spectroscopy.
- The Roman coronagraph instrument may be able to spectrally characterize atmospheres of small exoplanets in the Tau Ceti system.
- *Cross-Divisional Synergies:*
    - PEAS (Planet as Exoplanet Analog Spectrograph; Martin et al. 2020, Proc. SPIE 11447) will observe solar system planets as exoplanets.
    - Use of time series spectrophotometry of Earth from NASA EPOXI and DSCOVR missions to simulate time-varying spectra of rocky exoplanets and test retrieval of rotation period, surface & cloud variations, etc. (e.g., Jiang et al. 2018, AJ, 156, 26).

2.2. SCI-02: Modeling exoplanet atmospheres

- See SPA section 6 (atmospheres & biosignatures)
- Connects to Astro2020 Decadal Science Panel Questions E-Q1, E-Q2, E-Q3, E-Q4
- Connects to PSA2022 Decadal Science Questions 12.6, 12.10
- *Related gaps: SCI-13 for laboratory measurements of the physical and chemical properties of molecules and aerosols, SCI-14 for exoplanet interior structure and material properties, SCI-16 for advancing biosignature research to improve interpretation of spectra of potentially habitable worlds.*

Gap Summary:

Spectral modeling is essential for inferring the properties of exoplanet atmospheres, identifying their most crucial diagnostics, and defining the design goals for future telescopes and instruments. There are many complexities to model approaches, initial conditions, chemistry, energetics, and evolution of atmospheres such that many potentially relevant scenarios remain unexplored. Improving the fidelity of exoplanet atmosphere models and synthetic spectra can enhance the science return of JWST and HST observations (follow-up science), enhance the science return of Roman coronagraph and ARIEL/CASE (preparatory science), and refine understanding of the needed spectral resolution, S/N, or wavelength coverage that could influence the requirements for HWO (precursor science).

Capability Needed:

Ability to model the physical and chemical structure of exoplanet atmospheres and their emergent spectra across the range of planet masses, sizes, and stellar host types. Treat the effects of the total atmospheric pressure; chemical composition; presence of condensates, clouds & hazes; observer phase angle; and the radiative and energetic particle fluxes incident from the host star. Understand how the exchange of matter and energy between exospheres, lithospheres, hydrospheres, and potentially biospheres, affects the observed properties of the atmosphere today and over the planet's history. Challenges include determining composition of aerosols, understanding chemistry (e.g., relevant reactions, photochemistry, mixing, radiative transfer modeling (including scattering prescriptions), and 3D atmosphere dynamics (e.g., general circulation models). Modeling of the effects of greenhouse gases for assessment of surface temperatures and stability of surface water (habitability). Exploration of all the above parameters over a wide range of plausible exoplanetary atmospheres that might be discovered.

Capability Today:

- Thermophysical, radiative transfer, and photochemical models of planetary atmospheres in the solar system.
- Modeling of gas giant atmospheres accounting for varying formation mechanisms, protoplanetary disk chemistry, and migration.
- 3D circulation models of hot giant planets, modeling the impact of non-uniform cloud cover, modeling atmospheric chemistry and escape due to stellar XUV emission and predicted spectral observations (e.g., HST, JWST, future missions, etc.).
- Discrepancies have emerged between general circulation models that need to be reconciled (Fauchez et al. 2021, PSJ, 2, 106).

- Abiotic origins for molecular oxygen have been explored (e.g., June 2018 special issue of Astrobiology).
- See Madhusudhan (2019, ARA&A, 57, 617) review on pre-JWST landscape of exoplanet atmospheres modeling and observations and textbook by Heng (2017; "*Exoplanetary Atmospheres*").

Mitigations in Progress:

- Ongoing research by the community, with support from XRP, JWST, HST sources. *Cross-Divisional Synergies*: The Earth and solar system planets provide a prime opportunity for model validation. NASA ROSES XRP supports investigations exploring the remotely observable chemical and physical processes in exoplanet atmospheres, including theory.

2.3. SCI-03: Spectral signature retrieval

- *See SPA section 6 (atmospheres & biosignatures)*
- Connects to Astro2020 Decadal Science Panel Questions E-Q2, E-Q3, E-Q4, G-Q3
- *Related gaps: SCI-15 for effects of stellar photosphere heterogeneities on spectra*

Gap Summary:
Systematic effects in time series photometry and high contrast images limit the ability to extract reliable exoplanet spectra amidst backgrounds from residual instrumental signals (detector transients, stellar speckles) or from exozodi. The measured values of empirical parameters such as spectral slopes and linewidths can be affected, and the achieved spectral sensitivity may be worse than the photon noise limit. Early detections of molecular spectral features did not withstand reanalysis (e.g., Deming & Seager 2017, JGRP, 122, 53).

Pre-launch work to establish detection limits can be considered precursor science, while work to refine software or data-taking strategies would be preparatory science. Analysis of flight data to improve algorithms would be follow-up work.

Capability Needed:
Ability to reliably extract physical parameters, such as the atmospheric pressure-temperature profile and abundances of major atmospheric constituents. Quantify the effects of uncertainties in planet mass and radius on the derived atmospheric parameters, toward the goal of defining the mass measurement precision for gap SCI-08. Ability to model and subtract spatially varying exozodi backgrounds from exoplanet imaging spectra. Thorough understanding of the limits of the data, including effects of correlated and systematic noise sources. Strategies for data taking, calibration, and processing to mitigate these issues for each individual instrument/observatory and compilation of lessons learned for future work.

Capability Today:

- Community analyses of JWST, HST & Spitzer transit spectra and of imaging spectra from HST, JWST, and ground adaptive optics (e.g., GPI & SPHERE).
- Simple noise models predict JWST transit spectra and coronagraphic spectra.
- Development of best practices over time for acquiring exoplanet spectra with HST and application of them to JWST.
- Studies of contamination by stellar photospheric heterogeneities as a limitation to extraction of transiting exoplanet spectra (see gap SCI-15) and stellar speckles as a limitation to extraction of space-based imaging spectra of exoplanets (e.g., Rizzo et al. 2018, SPIE, 10698).
- Some understanding of the effects of model assumptions on retrieved parameters (Barstow et al. 2020, MNRAS, 493, 4884).
- Roman Space Telescope Science Investigation Teams conducted community data challenges for coronagraphic imaging.
- ExoPAG SAG 19 report defined new approaches to detection significance in high contrast imaging datasets.

Mitigations in Progress:

- The JWST Early Release Science Team for transit spectroscopy held a post-launch data challenge in March 2022 on simulated transit data sets, further information can be found at https://ers-transit.github.io/workshops.html .
- Best practices for JWST high contrast imaging have been compiled by Hinkley et al. (2023, arXiv:2301.07199).
- A data challenge for ground-based high contrast imaging is currently in its second phase (https://exoplanet-imaging-challenge.github.io/context2/).
- Gap topic is highlighted as a Precursor Science Gap for the NASA ROSES-2022 call Astrophysics Decadal Survey Precursor Science.

2.4. SCI-04: Planetary system architectures: occurrence rates for exoplanets of all sizes

- *See SPA sections: 2 (exoplanet populations), 3 (exoplanet dynamics), 5 (properties of target stars)*
- Connects to Astro2020 Decadal Science Panel Questions E-Q1, E-Q2, E-Q3
- Connects to PSA2022 Decadal Strategic Research Questions 12.2, 12.3, 12.4
- Related gaps: *SCI-05 Occurrence rates and uncertainties for temperate rocky planets ($\eta_\oplus$)*

Gap Summary: The structure of planetary systems is important for setting the context for conditions of exoplanets in the habitable zone, and more generally, for defining the range of outcomes of the processes of planet formation and evolution. Measurements of the distribution of planetary parameters (e.g., number of planets, their masses, radii, and orbital elements), from various techniques for stars of various types (e.g., stellar mass, multiplicity, metallicity, evolutionary state) are important both for constraining planet formation and evolution models, and for predicting science yields for future NASA missions. Planet formation and population synthesis models are needed for comparison against observations, to improve our understanding of formation and evolution, and to provide predictions for undetected planet populations that may be detectable with future observations. The lack of integrated exoplanet population studies limits our understanding of exoplanet demographics over a wide range of planet masses, radii, and orbital separations. Extrapolations to HZ demographics needs to be done from the most complete information available (see gap SCI-05). This is largely a preparatory science gap to enhance science return on current and future NASA missions.

Capability Needed:
Integrated exoplanet demographic results from different methods (e.g., transit, direct imaging, RV, and microlensing surveys). Include effects of completeness & reliability of Kepler detections, the low yield of direct imaging detections of self-luminous planets, microlensing results from recent campaigns. Update periodically to include new surveys (e.g., TESS) and methods (e.g., astrometry with Gaia) and to correct the host star properties used in prior studies. Extend temporal baselines of RV and transit surveys to discover longer-period planets and include astrometric constraints from combining Gaia & Hipparcos observations. The effect of measurement uncertainties on the results must be quantified. Practitioners of each technique should make sufficient occurrence rate metadata available for later combined analyses (Christiansen et al. 2023, ExoPAG SIG 2 report, arXiv:2304.12442). Planet formation and population synthesis models that account for the observed demographics, and in a form that can be readily used to synthesize “universes of exoplanets” for mission concept yield simulations (e.g., Habitable Worlds Observatory). Quantify the impact of stellar binarity on exoplanet frequency, as many potential direct imaging target stars are in multiple systems.

Capability Today:

- Ongoing microlensing, RV, transit, and direct imaging projects continue to build statistics on exoplanet frequency distribution. Examples: Pascucci et al. (2018, ApJ, 856, L28) study of distribution of mass-ratios of planets and their stars between microlensing and transit methods. Meyer et al. (2018, A&A, 612, L3) combined data from RV, microlensing, and imaging surveys to produce surface density distribution of gas giants in 1-10 M_{Jup} mass range for M dwarfs over longer-period planets. *Exoplanet Population Observation Simulator* (EPOS) compares synthetic planet population models to observations (Mulders et al. 2019, ApJ, 887, 157). Fernandes et al. (2019, AJ, 874, 81) combine transit, radial velocity, and direct imaging occurrence rate results to constrain a turnover in the distribution of giant planets to between 3-10 au.

- Community efforts to follow up accelerations of nearby stars calculated by combining Gaia & Hipparcos datasets, with e.g., direct imaging (e.g., Currie et al. 2023, Science, 380 198).
- A small number of studies have attempted to quantify the impact of stellar binarity on exoplanet frequency (e.g., Moe & Krautter 2021, MNRAS, 507, 5393).

Mitigations in Progress:

- Ongoing community efforts for assessing occurrence rates for close-in planets using Kepler, K2, and TESS data, reconciling results from different discovery methods (e.g., transit, radial velocity, microlensing, direct imaging), and factoring in Gaia stellar data.
- There is a large community effort to validate TESS exoplanet candidates.
- ExoPAG SIG 2 is monitoring available data on exoplanet occurrence rates and has released a first draft of a report with community recommendations for meta-data and additional data products to facilitate robust, reproducible demographics analyses.
- Community efforts measuring astrometric perturbations with Gaia and Hipparcos.
- ALMA studies of the structure of protoplanetary disks, and high contrast imaging searches for self-luminous exoplanets.
- Roman Space Telescope microlensing survey will measure occurrence rates for the cold planet population.
- Gap topic is highlighted as a Precursor Science Gap for the NASA ROSES-2022 call Astrophysics Decadal Survey Precursor Science.
- *Cross-Divisional Synergy*: Planetary science research on modeling the formation of solar system planets and other small bodies, and on the timing of their formation and migration.

2.5. SCI-05: Occurrence rates and uncertainties for temperate rocky planets ($\eta_\oplus$)

- *See SPA sections: 2 (exoplanet populations), 5 (properties of target stars)*
- Connects to Astro2020 Decadal Science Panel Questions E-Q1, E-Q2, E-Q3
- Connects to PSA2022 Decadal Strategic Research Questions 12.2, 12.3, 12.4
- Related gaps: SCI-04 (Planetary system architectures: occurrence rates for exoplanets of all sizes)

Gap Summary:

A critical parameter guiding the design of the HWO recommended by Astro2020, which must be capable of spectrally characterizing habitable zone (HZ) planets orbiting nearby stars, is *eta-earth* ($\eta_\oplus$) - the occurrence rate of rocky exoplanets in the habitable zones of FGK stars. Gap SCI-05 is the subset of gap SCI-04 focusing specifically on frequency of Earth-sized ($R_P \approx 0.8$-$1.4\ R_{Earth}$) planets in HZs. $\eta_\oplus$ remains considerably uncertain, with determinations from different authors varying by almost an order of magnitude. Better characterization of $\eta_\oplus$ will reduce uncertainty in estimated science yields (detection, spectroscopy) and reduce the risk that HWO might not achieve the ~25 spectrally characterized potentially habitable exoplanets called for by Astro2020. Measurements of trends in $\eta_\oplus$ as functions of stellar parameters like e.g., mass, multiplicity, metallicity, etc. could improve predictions of yield estimates. This is a precursor science gap affecting the level of risk to HWO achieving its prime science goal.

Capability Needed:

Observations, archival data analysis, and supporting theoretical research enabling improved constraints on $\eta_\oplus$, reducing uncertainty and potential biases. Detections of temperate rocky planets, and observations which can confirm the existence of candidate temperate rocky planets in Kepler data upon which $\eta_\oplus$ critically relies. Analysis of occurrence rates taking into account final Kepler products and improved stellar parameters, such that remaining uncertainties are dominated by intrinsic Kepler systematics. Ideally the values would be constrained and cross-checked via datasets other than Kepler, and trends sought as a function of system properties (e.g., stellar mass, multiplicity, presence of larger planets, etc.) to improve the fidelity of yield estimates. Development of an error budget for $\eta_\oplus$, identifying which terms contribute the most uncertainty and would be ripe for further improvement.

Capability Today:

Published analyses by several authors, including (e.g., Burke et al. 2015, ApJ, 809, 8; Traub 2016, arXiv:1605.02255; Hsu et al. 2019, AJ, 158, 109; Pascucci et al. 2019, ApJ, 883, L15; Bryson et al. 2020, AJ, 159, 279; Kunimoto & Matthews 2020, AJ, 159, 248). Gaia results have improved estimates of radii for all transiting planets (e.g., Fulton & Petigura 2018, AJ, 156, 264; Berger et al. 2018, ApJ, 866, 99). ExoPAG SAG 13 final report informed the LUVOIR and HabEx mission concept studies, who adopted $\eta_\oplus = 0.24^{+0.46}_{-0.16}$ for yield calculations, a factor of

3 systematic uncertainty. The most recent estimates from Bryson et al. (2021, AJ, 161, 36) have 68% confidence limits spanning 0.16 to 1.5 depending on assumptions about habitable zone and extrapolation of completeness for Kepler DR25 data. Bergsten et al. (2022, AJ, 164, 190) used updated stellar parameters informed by Gaia, final Kepler data products and candidate reliability, and attempted to account for the effects of atmospheric loss shaping the small planet population, yielded an occurrence rate estimate of $\Gamma_\oplus = 0.15^{+0.06}_{-0.04}$ ($\eta_\oplus \approx 0.09 \pm 0.03$).

Mitigations in Progress:

- The community is actively working on planet occurrence rate studies that incorporate final Kepler DR25 data and Gaia.
- ExoPAG SIG 2 (Exoplanet Demographics) remains active
- While TESS was not designed for exoplanet demographic surveys, the community is actively working on determining occurrence rates of terrestrial planets from TESS, particularly around M dwarfs.
- Gap topic is highlighted as a Precursor Science Gap for the NASA ROSES-2022 call *Astrophysics Decadal Survey Precursor Science*.
- *Cross-Divisional Synergy:* Improve understanding of the evolution of Venus and Mars to help inform limits on where habitable planets may be found orbiting other stars (i.e., empirical constraints on habitable zone).

2.6. SCI-06: Yield estimation for exoplanet direct imaging missions

- *See SPA section 2 (exoplanet populations)*
- Connects to Astro2020 Decadal Science Panel Question E-Q4
- *Related gaps: SCI-05 (Occurrence rates and uncertainties for temperate rocky planets, $\eta_\oplus$)*

Gap Summary:
The survey for temperate rocky exoplanets in more than 100 nearby habitable zones, called for by Astro2020, will be the largest single observing program of the HWO mission. An accurate definition of this survey will allow the goal of characterizing ~25 temperate rocky exoplanets to be achieved while preserving mission time for other priority science programs. Quantitative exoplanet science metrics, focusing on the yields of spectroscopically-characterized temperate rocky planets but also including aspects of comparative planetology, are needed to facilitate architecture trades for HWO.

This is a precursor science activity for HWO mission PDR, with subsequent refinements being preparatory science up through mission launch.

Capability Needed:
Capability within the NASA Exoplanet Exploration and Great Observatories Maturation Programs to calculate exoplanet science metrics, especially yield estimates, for exoplanet direct imaging missions using an open-source code for the simulator and with provision for community code contributions. The simulator should be implemented independent of mission architecture advocates, in support of the Great Observatories Mission and Technology Maturation Program (GOMAP) for HWO. Calculate mission yields and their uncertainties so that the ability of each architecture option to achieve the Decadal goal of characterizing ~25 potentially habitable worlds is understood, as well as the yields of other planet types. Community consensus is needed on the key astrophysical and instrument performance parameter inputs to the simulator (gaps SCI-04, SCI-05, SCI-11) and definitions of the exoplanet science metrics to be used.

Improved treatment of observation scheduling and mission rule optimization, in the use of precursor observations in planning imaging observations, and in estimating the significance of planet signals.

Capability Today:

- Adaptive Yield Optimization code employed in the HabEx and LUVOIR large mission studies by Stark et al. (2019, JATIS 5 4009).
- Public ExoSIMs code developed under the WFIRST Preparatory Science program by Savranksy & Garrett (2016, JATIS 2 1006), and applied in an independent analysis of LUVOIR and Habex yields by Morgan et al. (2019, JATIS 11117 01).
- Pre-decadal community yield study by the ExEP Standards Definition and Evaluation Team (Morgan et al. 2019, https://exoplanets.nasa.gov/ exep/studies/sdet/.
- Morgan et al. (2022, Proc. SPIE, 121802) presented yields for 6m class space telescope for coronagraph-only, starshade-only and hybrid architectures for several metrics, and accounting for possibility of prior EPRV survey knowledge.

- *Bioverse* (Bixel & Apai, 2021, AJ, 161, 228) is a new publicly available code for generating planets, simulating surveys and hypothesis testing.
- *ExoVista* (Stark, 2022, AJ, 163, 105) produces synthetic planetary systems and disks and simulates their physical parameters as a function of time.
- Simplified performance assumptions (coronagraph detection metrics, scheduling of starshade observations vs. planet orbital phase and L2 formation-flying dynamics) limit the accuracy of the results.
- ExEP organized the "Exoplanet Yield Modeling Tools Workshop" at AAS242 in Albuquerque in June 2023 to inform the community of, and encourage community development of, yield modeling capabilities. Recorded talks and tutorial materials were posted online[2].

Mitigations in Progress:

- Extended mission studies continue to support improvement in the fidelity of starshade operational scenarios toward the goal of approaching idealized mission yields.
- New imaging detection metrics (e.g., Jensen-Clem et al. 2018, AJ, 155, 19 and SAG 19 final report), more detailed starshade formation flying modeling (e.g., Soto et al. 2021, JATIS, 7, 2); and improved observation scheduling for starshades (Keithly et al. 2020, JATIS 6, 2) are ready to be incorporated into improved science yield estimates.
- Gap topic is highlighted as a Precursor Science Gap for the NASA ROSES-2022 call *Astrophysics Decadal Survey Precursor Science*.

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[2] https://exoplanets.nasa.gov/exep/events/456/exoplanet-yield-modeling-tools-workshop/

2.7. SCI-07: Intrinsic properties of known exoplanet host stars

- *See SPA section 5 (properties of target stars)*
- Connects to Astro2020 Decadal Science Panel Questions E-Q1, E-Q2, E-Q3, E-Q4
- Connects to PSA2022 Decadal Science Question 12.6d, 12.10
- *Related gaps: SCI-12 (Improvement of knowledge of transiting planet radii)*

Gap Summary:
The accuracies of measured exoplanet parameters needed for planetary characterization and interpretation of atmospheric spectra rely directly on the fidelity of stellar parameters derived from photometry, spectroscopy, astrometry, etc.

This is a follow-up activity once a confirmed planet is found by any detection technique.

Capability Needed:
Improved observational constraints on exoplanet and host star properties are needed to help inform the modeling of exoplanet atmospheres and interpretation of exoplanet spectroscopy (gap SCI-02). Stellar luminosity, age, high energy emission (e.g., UV, X-ray, flare properties), and stellar mass loss rates, help inform modeling of the evolution of the planet (and its star) and habitability studies. Time series observations of variable magnetic activity indicators (e.g., chromospheric activity, UV, X-ray) may be needed to constrain average values, which may also help with constraining age. Precision stellar abundances inform exoplanet formation and interior models. Knowledge of chromospheric activity and EUV emission inform models of atmospheric escape, and measurement of NUV and FUV emission informs modeling of atmospheric photochemistry. For terrestrial exoplanet studies in the near term, accurate elemental abundances and ages for M dwarf host stars are needed but have proved challenging. Basic stellar parameters (e.g., evolutionary status, mass, metallicity, etc.) are needed for non-exoplanet hosts to enable statistical studies. Improved knowledge of planetary system architecture, including stellar, substellar, or planetary companions, is helpful for interpretation of exoplanet properties and modeling. The ExoPAG SAG 17 report reviewed the observational needs re: stellar characterization for TESS candidates.

Capability Today:
NASA Exoplanet Archive contains compilation of confirmed and candidate exoplanets and their host stars, which can inform mission concept studies focusing on studying transits or transit spectroscopy/ photometry of previously known exoplanets, or direct imaging of previously known exoplanets. Gaia DR2 data on exoplanet host star properties ingested into NASA Exoplanet Archive. Gaia DR3 contains improved photometry (measured and synthetic), astrometry and parallaxes (distances), and spectroscopically derived effective temperatures, metallicities, surface gravities for exoplanet host stars. Hypatia Catalog Database compiles stellar chemical abundance data for thousands of stars including mission target stars and >1300 exoplanet host stars.

Mitigations in Progress:

- NASA Exoplanet Archive is actively compiling data on exoplanets and their host stars.
- The ExoPAG SAG 22 report listed sets of stellar properties and data that should be obtained, cataloged, maintained, improved, and curated for exoplanet host stars, including the targets of future missions.
- CUTE cubesat launched in 2021 and its 4-yr mission will measure NUV transit spectroscopy of close-in transiting planets to constrain exoplanet mass-loss rates and atmospheric composition.
- SPARCS cubesat is scheduled to launch in 2024 to monitor NUV and FUV emission (and variability) for M dwarfs of a wide range of ages.

Note: Gap SCI-12 is for improving knowledge of exoplanet radii (especially for deblending the contributions from stellar companions, both physical and unphysical), whereas gap SCI-07 focuses on improving knowledge of other stellar parameters to help inform the interpretation and modeling of exoplanet data (e.g., spectra).

2.8. SCI-08: Mitigating stellar jitter as a limitation to sensitivity of dynamical methods to detect small temperate exoplanets and measure their masses and orbits

- *See SPA sections: 3 (exoplanet dynamics), 5 (properties of target stars)*
- Connects to Astro2020 Decadal Science Panel Questions E-Q1, E-Q2, E-Q3, E-Q4, G-Q3
- Connects to PSA2022 Decadal Science Question 12.11
- Related gaps: *SCI-09 Dynamical confirmation of exoplanets, measuring their masses & orbits*

Gap Summary:
Measurements of masses and orbits are crucial for characterizing exoplanets, and for modeling their spectra and composition. Radial velocity and astrometry methods are anticipated to be the primary means of measuring masses in support of HWO reconnaissance of exoplanet atmospheres. Both techniques suffer from stellar noise ("jitter") from multiple sources over a range of timescales, and for PRV the stellar noise currently dominates the uncertainty budget below 1 m/s - currently precluding reliable detection of temperate Earth-mass exoplanets around Sun-like stars. EPRV could provide a mix of preparatory and/or follow-up capability for detecting planets (including small potentially habitable worlds), constraining their orbits and measuring masses. The degree to which EPRV can contribute capability for characterizing ~Earth-mass temperate planets by the time of HWO is unclear (although the EPRV Working Group has presented a community pathway). This is a precursor science topic as advancing EPRV and astrometry techniques, or improving our knowledge of their limitations for implementation, can inform the strategy for designing the programmatic context of capabilities needed to provide mass/orbit measurements for the small exoplanets HWO is designed to study.

Note: Technology needs for EPRV and astrometry are tracked separately in the ExEP Technology Gap List.

Capability Needed:
Clarification on the exoplanet mass strategy for HWO by late 2020s and advancement of EPRV and astrometric capabilities. *What mix of mass-measuring capabilities (EPRV and astrometry) - with what instruments - and when - will be able to provide either prior or posterior knowledge of exoplanet masses and orbits to inform HWO targeting for its survey for potentially habitable worlds and other exoplanets, and modeling of the observed reflected-light exoplanet spectra?* This question can be broken down into parts:

- To what extent - and to what accuracy - do we need to measure the masses and orbits of exoplanets that will be imaged and spectrally characterized with HWO?
- Can EPRV be advanced sufficiently to enable reliable measurement of Earth-like exoplanets orbiting Sun-like stars to inform the HWO HZ survey?
- Could the HWO itself provide sub-microarcsecond astrometry measurements to sufficient accuracy to provide masses of potentially habitable worlds? Or are other options needed?

For reference, among the nearest, brightest plausible ~100 HWO targets for a survey of potentially habitable worlds, the median target is a 5th magnitude Sun-like (~1.0 M_{Sun}) star at d ~ 10 pc, and an Earth twin around a solar twin would produce a radial velocity amplitude of ~9 cm/s (independent of distance & brightness) or astrometric amplitude of 0.3 microarcsecond.

EPRV: RV jitter intrinsic to the star is at ~m/s level, and higher for active stars (see EPRV WG report). Extreme PRV (EPRV) requires precision below 10 cm/s but accuracy at ~cm/s level so that systematic errors do not dominate. Major commitments of observing time on telescopes with PRV spectrographs are needed. Need new analysis methods to correct for stellar RV jitter using high spectral resolution and broad spectral coverage. Solar feeds on new spectrographs and solar PRV datasets enable testing and improvement of mitigation strategies. Reaching requisite velocity precision for characterizing temperate rocky planets for stars hotter than mid-F, and/or with high *v*sini, representing tens of % of nearby direct imaging targets is prohibitive with EPRV, and astrometry may be required. ExoPAG SAG-8 (Plavchan et al. 2015; arXiv: 1503.01770) assessed capabilities and future potential for precision radial velocity for exoplanet detection and characterization (e.g., measuring bulk densities of transiting exoplanets) relevant to NASA missions. Extreme Precision Radial Velocity Working Group Final Report (2021; https://arxiv.org/abs/2107.14291) provided a modern roadmap to NASA and NSF for advancing the EPRV technique in support of a direct imaging space telescope (i.e., HWO).

Astrometry: Predicted astrometric amplitudes for 1 M_{Earth} planets at the Earth Equivalent Instellation Distance (EEID) for plausible HWO target stars are mostly between 0.1-1 microarcsec. For Sun-like activity levels, astrometric jitter would be ~0.05 microarcsec – small, but not negligible (and higher for more active stars).

Capability Today:

PRV: Single measurement precision (SMP) among ongoing RV surveys is summarized in Fischer et al. (2016, PASP, 128, 066001) and updated SOA capabilities were presented at EPRV5 workshop in Santa Barbara (March 2023). Reported SMPs for ESPRESSO (Pepe et al. 2021, A&A, 645, A96) and EXPRES (Petersburg et al. 2020, AJ, 159, 187) are near ~30 cm/s on timescales of months. Smallest claimed RV amplitudes detected today are ~35 cm/s for Tau Ceti (Feng et al. 2017, AJ, 154, 135). Collier Cameron et al. (2021, MNRAS, 505, 1699) demonstrated the feasibility of reliably measuring RV signals with K=40 cm/s for the Sun Machine learning techniques have shown promise in reducing jitter on simulated and real solar datasets (e.g., Jones et al. arXiv:1711.01318, de Beurs et al. arXiv:2011.00003).

Astrometry: Studies on stellar astrometric jitter of stars and the Sun during development phases for SIM and Gaia. Existing ground-based astrometry (CHARA, NPOI, VLTI) cannot reach the required accuracy.

Mitigations in Progress:

- Major NASA investment in PRV instrument (NEID) for WIYN (northern hemisphere 4-m class). NEID was commissioned (stability demonstrated to <50 cm/s), and data for RV standard stars is being made public immediately. Archiving NEID solar data and investigating options to archive EXPRES solar data.

- EXPRES and MAROON-X have came online and are demonstrating <1 m/s performance over multi-month timescales.
- KPF (funded by NSF) was commissioned on Keck in late 2022 and will be available to the US community through NASA Keck time.
- NASA funded a second EPRV Foundation Science grant opportunity in ROSES 2022, with selections expected in summer 2023.
- Following recommendations from the Exoplanet Science Strategy (2018) and EPRV WG report, and in support of the Astro2020 Decadal scientific vision to "*identify and characterize Earth-like extrasolar planets*" ("*Pathways to Habitable Worlds*"), and to scientifically support future use of HWO to fulfill its Decadal goal to search for habitable zone planets and search for biosignatures, ExEP is sponsoring the *EPRV Research Coordination Network*[3]. The EPRV RCN aims to increase communication and collaboration in the radial velocity community in order to advance the EPRV technique towards the goal of detecting temperate, small planets around Sun-like stars. The RCN already includes over 100 members, and has regular virtual meetings and a colloquium series on topics like instrumentation, observations/surveys, data analysis techniques (e.g., stellar variability mitigation techniques, etc.), solar studies, etc.

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[3] https://exoplanets.nasa.gov/exep/NNExplore/EPRV-RCN/EPRV-RCN-welcome/

2.9. SCI-09: Dynamical confirmation of exoplanet candidates and determination of their masses and orbits

- *See SPA sections: 2 (exoplanet populations), 3 (exoplanet dynamics), 5 (properties of target stars), 6 (atmospheres & biosignatures)*
- Connects to Astro2020 Decadal Science Panel Questions E-Q1, E-Q2, E-Q3, E-Q4
- Connects to PSA2022 Decadal Science Question 12.11
- Related Gaps: *SCI-08 (Mitigating Stellar Jitter)*

Gap Summary:

The majority of current exoplanet discoveries have been made via the transit method, e.g., Kepler, K2, TESS. However, transit observations typically do *not* constrain the planetary mass (except for rare cases where transit-timing variations [TTVs] can), which is crucial for understanding the planetary bulk density / composition and interpreting atmospheric spectra. RV observations usually need to be made to obtain mass measurements. Orbital ephemerides need to be known precisely enough to support scheduling of transit and eclipse spectroscopy.

This is a follow-up activity for exoplanets not discovered via the radial velocity method.

Capability Needed:

There are insufficient precision RV resources available to the community to follow up all K2 and TESS candidates that may be relevant to spectroscopic studies with JWST and ARIEL/CASE. Follow up of K2 and TESS candidates starts with quick-look low-precision RV screening for false positives (e.g., eclipsing binaries), then high precision PRV to determine masses of the best candidates. TESS follow-up requires RV observing time in N and S hemispheres, sufficient to cover the expected 12.5k TESS candidates of which ~1,250 should be detected in the 2-min cadence data, with ~18 smaller than 2 R_{Earth} and in the habitable zone (Kunimoto et al. 2022, AJ, 163, 290). Continuation of the TESS extended mission, and/or targeted transit followup with other facilities, to refine transit ephemerides sufficiently for predicted transit time accuracy better than 1 hour through the epochs of the ARIEL/CASE mission.

Capability Today:

TESS has achieved the main goal for its primary mission of detecting ~50 exoplanets smaller than Neptune and measuring their masses. Follow-up of TESS science team targets is ongoing with RV facilities including Magellan/PFS, HARPS, HARPS-N and ESPRESSO for precise follow-up at ~1 m/s precision. ESPRESSO has demonstrated RV precision of ~28 cm/s over a night and ~50 cm/s over several months for HD 85512, with instrument precision of ~10 cm/s, and there is ESPRESSO-GTO survey of ~50-100 K2/TESS planets ($<2R_{\text{Earth}}$, $V < 14.5$ mag; Pepe et al. 2021, A&A, 645, 96). For instruments with demonstrated <1 m/s RV accuracy, there is limited US community access, and only in northern hemisphere (e.g., NEID, MAROON-X). TTV: e.g., analysis of Kepler multi-planet systems; Spitzer Exploration Program Red Worlds campaign observed transits over 1000+ hrs for 7-planet TRAPPIST-1 system (Ducrot et al. 2020, A&A, 640, A112, and Agol et al. 2021, PSJ, 2, 1).

Mitigations in Progress:

- NASA-NSF Partnership for Exoplanet Observational Research (NN-EXPLORE). NASA supported construction of NEID instrument, now operational on Kitt Peak but slowed by the pandemic and local forest fires. NN-EXPLORE is supporting US community access to SMARTS 1.5-m CHIRON and MINERVA-Australis.
- NASA supports community access to Keck HIRES and now KPF instruments (starting 2023), which will include queue-based scheduling.
- Options for additional southern hemisphere community PRV access continue to be explored.
- TESS was approved for a second mission extension in the 2022 Senior Review.

2.10. SCI-10: Precursor observations of direct imaging targets

- *See SPA sections: 3 (exoplanet dynamics), 5 (properties of target stars), 6 (atmospheres & biosignatures)*
- Connects to Astro2020 Decadal Science Panel Questions E-Q1, E-Q2, E-Q3, E-Q4
- Related Gaps: *SCI-07 (Properties of Exoplanet Host Stars)*

Gap Summary:
Preparatory observations benefit future exoplanet missions like HWO by 1) screening for background sources and close-in, low-mass stellar and substellar companions that might compromise exoplanet imaging sensitivity; 2) detecting exoplanets for future characterization, or setting observational and/or dynamical limits on their presence; 3) measuring stellar physical properties, chemical abundances, and radiation environments to enable accurate planet characterization including interpretation of exoplanet spectra (see gap SCI-07); and 4) identifying systems with high exozodi levels where spectroscopy of small exoplanets may not be possible (see gap SCI-11).

Capability Needed:
A census and characterization of plausible HWO target systems, including their stellar and substellar companions which may dynamically limit the presence of planets in their habitable zones. Theoretical research constraining the stability of planets in the habitable zones of HWO targets. Assess the bound companion (stellar and substellar) detection limits provided by existing data (e.g., RV, Gaia astrometry, etc.). With the goal of detecting temperate rocky exoplanets in the target systems and other planets that may affect the dynamical stability of planet orbits in habitable zones, conduct PRV observing programs in both N and S hemispheres (executed consistently over > 5 years, ideally through HWO launch and survey), and conduct observations using other techniques which may feasibly detect small planets orbiting nearby target stars (including e.g., astrometry, and high-contrast IR imaging). Constraints on stellar multiplicity from high resolution imaging, RV and astrometry (e.g., Gaia), are needed to assess whether high contrast imaging will be feasible, as starlight suppression performance is affected by the presence of close neighboring stars. Uniform determination of stellar properties across the target sample in both hemispheres. Sufficiently sensitive X-ray and far-UV characterization of stellar radiation environments in the target systems.

Capability Today:
The census of even massive companions (low-mass stars, brown dwarfs, giant planets) is still incomplete for plausible HWO targets, let alone for small exoplanets. The HabEx and LUVOIR teams conducted yield simulations based on the Hipparcos star catalog with limited binary star info and initial estimates of key stellar astrophysical parameters. Binary orbits in the nominal target systems are poorly characterized, including several cases where Gaia failed to confirm companions reported in double star catalogs. Limited far-UV and X-ray observations are available for plausible HWO target stars. In recent years, ExEP recently supported two studies analyzing archival PRV data for direct imaging targets. Howard & Fulton (2016, PASP, 128, 4401) completed a RV analysis to search for bound companions for stars in the 2014 versions of Roman CGI, Exo-S, and Exo-C target lists using data from California planet search (many of which are plausible HWO targets). A similar analysis using archival data from six instruments

for Southern HabEx/LUVOIR/HWO targets was conducted by Laliotis et al. (2023, AJ, 165 176). There are published (and unpublished) RV data for many potential Roman Space Telescope/CGI targets. Butler et al. (2017, AJ, 153, 208) published 61k RVs measured over 20 years for stars in Lick-Carnegie Exoplanet Survey, including many mission targets. NASA/NSF EPRV Working Group has recommended a strategy for a precursor observing program. Facilities: e.g., Keck HIRES, Lick APF, HARPS, HARPS-N, PFS-Magellan, EXPRES, MAROON-X, NEID. KPF commissioned and available for the community through NASA Keck time in 2023. Wagner et al. (2021, Nature Comm. 12, 922) VLT/NEAR observations of α Cen A demonstrates current ground imaging IR sensitivity limits to planets around nearest targets. *Precursor catalogs*: The ERPV Working Group had sorted the pre-Astro2020 imaging mission study targets according to each star's suitability for extreme-precision Doppler measurements.

Mitigations in Progress:

- ExoPAG SAG 22 report includes recommended datasets to complete host star characterization.
- A catalog of the most likely target stars where small temperate planets could be imaged by a 6-m HWO was posted to the NASA Exoplanet Archive in early 2023**,** to encourage community observations and analysis of these systems (documentation is available on ExEP science page[4]). The catalog will be periodically updated to account for community input. The NEID GTO program on WIYN is surveying ~20% of these NASA Mission Targets.
- EXPRES GTO program on LDT is surveying ~10-15% of NASA Mission Targets.
- Priority of precursor work on Roman CGI targets is unclear due to the instrument's tech demo status. Gaia mission Data Release 3 in June 2022 allowed astrometric accelerations to be identified for a large number of stars (e.g., Kervella et al., 2022, A&A, 657, 7; Feng et al. 2022, ApJ, 262, 21), some of which may be good targets for direct imaging discovery of low-mass companions.
- Gaia DR4 (not before the end of 2025) is expected to reveal astrometric perturbations by giant exoplanets for thousands of stars, some of which could be targets for direct imaging.
- Many of the target stars are being searched for close stellar companions by optical speckle imaging.
- Gap topic is highlighted as a Precursor Science Gap for the NASA ROSES-2022 call *Astrophysics Decadal Survey Precursor Science*.

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[4] https://exoplanets.nasa.gov/exep/science-overview/

2.11. SCI-11: Understanding the abundance and distribution of exozodiacal dust

- *See SPA section 4 (exozodiacal dust)*
- Connects to Astro2020 Decadal Science Panel Questions E-Q1, E-Q2, E-Q3, E-Q4
- Related gaps: *SCI-03 (Spectral signature retrieval)*, *SCI-06 (Mission yield simulations)*

Gap Summary:

Exozodiacal dust is a noise source that compromises imaging and direct spectroscopy of small planets in and around the habitable zones of nearby stars. It can be much brighter in a telescope resolution element than exoplanetary signals that the HWO will be designed to measure. Substructure in the exozodi distribution may mimic the presence of an exoplanet and thus confuse searches made with smaller telescope apertures, or of more distant targets. To date, substructure in the distribution of habitable zone dust has been mapped only for the case of our own solar system.

Reducing the uncertainty in the median and distribution of exozodi levels and addressing the risk that the presence of hot dust may affect scattered light levels in the HZ, are precursor science activities. Other activities cited here are preparatory.

Capability Needed:

Statistical knowledge of exozodiacal dust levels in the habitable zone relative to the level in our solar system is needed for nearby FGK stars that will be the targets of the HWO. Further observational work that reduced the uncertainty in the median exozodi level would reduce the risk that HWO's survey of nearby habitable zones would consume too large a fraction of the prime mission, that the mission lifetime might need to be increased, or that the mission might produce lower-quality spectra than intended. Theoretical modeling of dust sources & sinks, dust transport processes, and dynamical sculpting by planets. Mission yield simulations of how exozodi levels and uncertainties affect the integration times and achievable signal-to-noise ratios for exoplanet detection and characterization, as a function of mission architecture. Simulations of scenes as viewed by future imaging missions, quantifying the effectiveness of multi-epoch observations to discriminate exozodi clumps from planets. Directly observed scattered light images of exozodi disks in habitable zones would be very valuable, if they were sensitive down to the ~5 zodi level, were obtained for stars with measured 10 μm excess (potentially enabling dust albedo estimates), and had the resolution to show substructures and validate theoretical simulations. An understanding of the physical relationship (if any) between the hot dust emission detected by near-IR interferometers and the population of small grains in habitable zones.

Capability Today:

Images are available showing the substructure of cold (Kuiper Belt) debris disks as seen by HST, ground adaptive optics, Herschel, and ALMA. Hot dust emission is detected in many systems with near-IR interferometry but its origin and relevance to habitable zone dust is not understood. There is a rich literature of theoretical models of debris disk structure treating such effects as dust radial transport and planetary perturbations on debris disk structure. The LBTI HOSTS survey has measured the mid-IR excess emission due to warm exozodiacal dust in the habitable zones of 38 stars (Ertel et al. 2020, AJ, 159, 177), deriving a median exozodi level 3 times that of the solar system but with a significant $+1\sigma$ uncertainty of 6 zodis. Detection upper limits for individual FGK stars are only ~120 zodis, however. While the yields of exoplanet direct imaging missions are a weak function of the exozodi level (Stark et al. 2015, ApJ, 808 139), the quality of spectra of Earth analogs can become problematic for the more distant targets if the exozodi level is $> +1\sigma$ from the LBTI median result. It is currently unclear whether the presence of hot dust in some systems poses a threat or not to detection of temperate rocky exoplanets.

Mitigations in Progress:

- The Astro2020 Decadal Survey was silent on whether additional investments in exozodi measurements should be a priority. Options for further observational work include:
  - The LBTI instrument team has studied possible upgrades that would increase the sensitivity of their instrument by a factor of ~3.
  - Roman coronagraph scientists published a paper (Douglas et al. 2022, PASP 134 :024402) quantifying the sensitivity the instrument might be able to achieve to exozodiacal dust in a survey of nearby stars, should NASA decide to conduct a science program with that instrument.
  - Current near-IR interferometers and upcoming ELTs will have capabilities to constrain warm exozodi levels and these are still being assessed.
- The first VLTI/MATISSE measurements are providing L band visibility constraints on hot dust. A new nulling interferometer under development for the VLTI "NOTT" will provide higher S/N detections of hot exozodiacal dust in the L band circa 2025.
- NASA XRP is funding theoretical studies and observational efforts to connect various observables.
- Gap topic is highlighted as a Precursor Science Gap for the NASA ROSES-2022 call *Astrophysics Decadal Survey Precursor Science*.
- *Cross-Divisional Synergy:* research on interplanetary dust grains, understanding source dust populations and distribution of dust in the solar system.

2.12. SCI-12: Measurements of accurate transiting planet radii

- *See SPA sections: 2 (exoplanet populations), 5 (properties of target stars)*
- Connects to Astro2020 Decadal Science Panel Questions E-Q1, E-Q2, E-Q3, E-Q4
- Related gaps: *SCI-07 Properties of Exoplanet Host Stars*

Gap Summary:
Accurate measurements of exoplanet radii are important for: properly characterizing exoplanets, estimating bulk densities, modeling their compositions, atmospheres, spectra, and the discovery of trends important to understanding planet formation and evolution. The accuracy of transiting exoplanet radii is most often limited by the accuracy of measured stellar radii, which can be dominated by the blending effects from neighboring stars. For small exoplanets (i.e. with shallow transits), planet radii accuracy is limited by low S/N, and degeneracies between star-planet radius ratio, limb darkening, and transit impact parameter. Not accounting for light contamination by companions or neighboring stars, or poor stellar characterization, can lead to exoplanet radii systematically miscalculated at the tens % level. AO and speckle imaging validation of Kepler prime mission candidates took ~3 years to complete. TESS has now exceeded the number of Kepler+K2 candidates, and thus needs a similar long-term effort to determine precise exoplanet radii. *Note:* Improvement in knowledge of other stellar parameters relevant to interpreting exoplanet data is outlined separately in gap SCI-07.

This is follow-up science for Kepler, K2, and TESS, while also being preparatory science for JWST and ARIEL/CASE.

Capability Needed:
Detailed observations are needed to derive accurate stellar radii, including high res spectroscopy, high resolution imaging, and seeing-limited photometry to identify false positives (i.e., variable stars). High resolution imaging in bulk to validate thousands of TESS and K2 candidates, at least for candidates sufficiently bright and suitable for characterization or demographic studies. For those stars, access to observatories equipped with AO or speckle imaging cameras and reduction pipelines, is needed in both N and S hemispheres. Support work that improves estimation of stellar and exoplanet parameters for discovered exoplanet systems. Supporting photometric and spectroscopic stellar data, along with astrometric, photometric, and spectroscopic data from latest Gaia data releases, are critical for accurately assessing stellar parameters – and exoplanet radii. In some cases, asteroseismic analysis of light curves can improve estimates of the star's density, improving estimates of a/R, improving constraints on transit radius ratio (along with limb darkening and impact parameter). For occurrence rate studies, accurate limiting radii for planet detection for transit survey stars for which transiting planets were not detected is also important. Estimates of orbital periods for single transit planet candidates can be measured (improved) as well when a star's density is constrained (improved). See ExoPAG SAG 17 report discussing resource needs for TESS follow-up to constrain stellar and exoplanetary radii.

Capability Today:
NESSI speckle camera at WIYN, and Zorro and 'Alopeke cameras on Gemini S and N, respectively, and NIRC2 on Keck, offer ability to screen a subset of targets to very small separations. Other community resources include SOAR HRCam (speckle), and various ground-

based AO observations with e.g., Robo-AO, VLT/NACO, etc. have helped validate KOIs, K2 candidates, and TOIs. TESS Follow-up Program includes Las Cumbres Obs. Network (photometry and spectroscopy), MEarth (photometry) and TRES (spectroscopy). Gaia photometry & astrometry resolves well-separated multiples and provides parallaxes that have greatly reduced the uncertainty in intrinsic stellar radii. High resolution spectroscopy can reveal spectroscopic binaries, and can provide precise stellar parameters, particularly when coupled with Gaia data. Injection and recovery tests can place further quantitative constraints on companions. For improving knowledge of host star T_{eff}, metallicity, gravity: high-resolution spectroscopy surveys (e.g., California-Kepler survey), lower resolution spectroscopy surveys (e.g., APOGEE & LAMOST), and community access to spectrographs for extracting stellar spectra (e.g., Keck HIRES, NEID, CHIRON, etc.).

Mitigations in Progress:

- Ongoing NASA support for community access to optical speckle cameras on WIYN, Gemini-N and Gemini-S, as well as near-IR AO imaging with Keck/NIRC2.
- Community seeing-limited and high contrast imaging observations supporting TESS follow-up.
- ExoFOP is supporting community work in this area through coordination of observations, and the sharing of data and derived results.

Note: Gap SCI-12 is for improving knowledge of exoplanet radii (especially for deblending the contributions from stellar companions, both physical and unphysical), whereas SCI-07 focuses on improving knowledge of other stellar parameters to help inform the interpretation and modeling of exoplanet data (e.g., spectra).

2.13. SCI-13: Properties of atoms, molecules and aerosols in exoplanet atmospheres

- *See SPA section 6 (atmospheres & biosignatures)*
- Connects to Astro2020 Decadal Science Panel Questions E-Q1, E-Q2, E-Q3, E-Q4
- Connects to PSA2022 Decadal Science Question 12.6
- *See gap SCI-02 for atmosphere modeling issues beyond the properties of its constituents*

Gap Summary:
Understanding and interpreting the full gamut of upcoming exoplanet spectra from JWST, Roman CGI, ARIEL/CASE, and the exoplanet direct imaging mission prioritized by Astro2020 will hinge on our ability to link observations to theoretical atmosphere models. These models rely on understanding the optical properties of atoms, molecules and aerosols, as well as the reaction rates between relevant chemical species. Together these properties shape our understanding of the chemistry and climate of exoplanet atmospheres.

This is precursor science supporting atmosphere modeling which can define HWO spectroscopy requirements, and can be follow-up science if observed spectra show new or poorly-modeled features.

Capability Needed:
Ability to perform theoretical calculations of key molecular and atomic spectroscopic properties in relevant physical conditions including effects of pressure broadening. Challenges include obtaining lab measurements or performing ab initio calculations of line intensities, line positions, pressure or collisional broadening, and partition functions. Ability to perform theoretical calculations and/or laboratory measurements of gas spectra, reaction rate coefficients, and aerosol properties in relevant physical conditions. Ability to obtain refractive indices of aerosol properties in relevant physical conditions. See white papers by Fortney et al. (2016; arXiv: 1602.06305) and Wolf Savin et al. (2019, BAAS 51, 3, 96).

Capability Today:
Ab initio line list calculations of several dozen molecules with the ability to correct line positions. Laboratory measurements of line lists at low temperatures. Reaction rate coefficients measured at high combustion temperatures and standard Earth temperatures. Publicly available opacity databases with limited effects of pressure or collisional broadening. Curated exoplanet aerosol database of refractive indices (provided by HITRAN) over limited wavelength ranges.

Mitigations in Progress:
- Several exoplanet specific efforts to expand accuracy and parameter space of line list data (e.g., HITRAN/HITEMP, Ames, ExoMol, TheoReTS).
- Funded collaboration between HITRAN/ExoMol and exoplanet theory groups to develop community tools and best practices for computing and disseminating opacity data.
- XRP-supported programs on measuring spectroscopic line lists, absorption cross-sections, etc. for common molecules in atmospheres of hot planets and brown dwarfs relevant to impending JWST observations.

- Gap topic is highlighted as a Precursor Science Gap for the NASA ROSES-2022 call *Astrophysics Decadal Survey Precursor Science*.

2.14. SCI-14: Exoplanet interior structure and material properties

- See SPA section 6 (atmospheres and biosignatures)
- Connects to Astro2020 Decadal Science Panel Questions E-Q1, E-Q2, E-Q3, E-Q4
- Connects to PSA2022 Decadal Science Question 12.5, 12.7
- Related gaps: *SCI-02 (Modeling exoplanet atmospheres)*

Gap Summary:
Improved understanding of interior structure across the mass/radius diagram would be valuable for interpreting the results of current and future exoplanet missions. Exoplanets exhibit a wide range of densities beyond those seen in the solar system. Tenuous "super puffs", extremely dense planets, and the wide range of radii observed over the mass range of ~2-10 M_{Earth} and their trends with orbital radius, all pose challenges to models of exoplanet structure, composition, formation, and evolution. The application of planetary interior, formation, and evolution models is hampered by uncertainties in the measured or numerically-predicted material properties under the relevant physical conditions, including the solubility of gases which can be exchanged with the atmosphere, and including conditions experienced transiently during planet formation.

This is largely follow-up science to model the interiors of planets with mass, radius, and/or atmospheric composition measurements.

Capability Needed:
Experimental measurements and theoretical calculations of material properties (e.g., equations of state, transport properties, mixing properties, etc.) under the pressure-temperature conditions found in exoplanets (super-Earths, sub-Neptunes, and cores of giant exoplanets). Development of dynamic compression experiments that simulate the pressure and temperature conditions in deep interiors. Access to material properties data (e.g., phase relationships, thermodynamic properties) in an organized format and robust modeling tools over a wide range of pressures, temperatures, and compositions (e.g., water, ammonia, methane ice, silicate-ice mixtures, silicate-hydrogen mixtures, hydrogen/helium etc.).

Capability Today:
Facilities to explore Earth-interior pressures already exist. Ab initio computer simulations exist but not with broad application. Only limited data exist beyond solar system planet conditions. Theoretical modeling of exoplanet interior evolution, suite of models across varying planet density, internal heat flux, starting compositions (e.g., Thorngren et al. 2016, ApJ, 831, 64; Lopez & Fortney 2014, ApJ, 792, 1; Dorn et al. 2018, ApJ, 865, 20).

Mitigations in Progress:
- NASA ROSES XRP supports investigations to explore the chemical and physical processes of exoplanets (including state and evolution of surfaces, interiors, and atmospheres).
- NASA Astrobiology/ICAR includes support for research on how volatiles are exchanged between the atmosphere, surface, and interior of exoplanets. NExSS workshops like NExSS/NAI/NSF Joint Workshop "Upstairs Downstairs: Consequences of Internal Planet Evolution for the Habitability and Detectability of Life on Extrasolar Planets" (2016),

"Habitable Worlds 2017: A System Science Workshop", and NExScI-supported "Exoplanet Demographics" (2020).

- *Cross-Agency Synergies:* Center for Matter at Atomic Pressures (CMAP) is a new NSF Physics Frontier Center designed to connect observational and laboratory scientists to address the high pressure microphysics relevant to exoplanetary interiors.
- *Cross-Divisional Synergy*: support for Earth Science research on constraining interior composition and structure of Earth, and Planetary Science research on the same for the terrestrial planets (e.g., InSight), gas giants (e.g., Juno), and ice giant planets.

2.15. SCI-15: Quantify and mitigate the impacts of stellar contamination on transmission spectroscopy for measuring the composition of exoplanet atmospheres

- Connects to Astro2020 Decadal Science Panel Questions E-Q1, E-Q2, E-Q3, E-Q4, G-Q3
- Related Gaps: *SCI-03 (Spectral signature retrieval)*

Gap Summary:
Transmission spectroscopy is an important method for probing the composition and structure of the atmospheres of exoplanets, and for the next two decades will be the primary means of studying the atmospheres of small rocky exoplanets. The method relies on time-series stellar spectroscopy, monitoring wavelength- dependent brightness variations. However, the stellar disk that the planet crosses is heterogeneous, with spatial and temporal variations in emission from the photosphere, chromosphere, spots, faculae, and plages - whose effects can conspire to mimic some molecular band features expected for exoplanets. To exploit observations with current (e.g., HST, JWST) and future (e.g., ARIEL, HWO) space observatories, we need to be able to quantify the degree of stellar contamination and develop mitigation strategies.

This is follow-up science to understand the limits of exoplanet transmission spectroscopy data for individual stars.

Capability Needed:
ExoPAG SAG 21 report (Rackham & Espinoza et al., 2022, arXiv:2201.09905) presents detailed needs regarding the stellar contamination issue for advancing the transmission spectroscopy technique. Theoretical and observational research on time-varying properties of spots, faculae, and granules in vis/IR (0.3-5μm) for the Sun and exoplanet host stars of varying type and activity. Include MHD modeling to provide priors on spectra of spots and faculae for stars of varying parameters, validation of 3D granulation simulations against vis/IR observations of Sun and other stars. Long time baseline panchromatic observations of Sun and stars to inform models of the stellar atmospheres and its heterogeneities, and synthetic spectra (unresolved disk, and transit chords). Best practices are needed for including stellar heterogeneity into transit modeling and atmospheric retrievals. A consensus needs to emerge on the practical limits to the detection of exoplanet spectral features, and which exoplanet spectral features are the least susceptible to stellar contamination.

Capability Today:
See SAG 21 report (Sec. 2) for extensive review on current capabilities. Observations of spot occultations from ground and space (e.g., Kepler) have enabled joint analyses of the properties of the transiting planet and star and its surface phenomena.

The SAG 21 report lists numerous publicly available starspot occultation codes and recent work on the subject. Some recent examples include: Herbst et al. (2021, ApJ, 907, 89) presents updated empirical relations for starspot temperature and area for FGKM stars. Johnson et al. (2021, MNRAS, 504, 4751) fit Kepler light curves of variable cool stars using models of time-varying faculae and spots and employing 3D magnetoconvection models. Barclay et al. (2021, AJ, 162, 300) demonstrated that starspot contamination could plausibly account for the claimed detection of H_2O for K2-18b.

Mitigations in Progress:

- *Pandora* smallsat (launch date 2025; Quintana et al. 2021, arXiv:2108.06438) will collect simultaneous visible photometry and NIR spectroscopy data for transiting exoplanets of K/M dwarf stars, allowing the effects of spots along the transit chord to be assessed.
- NSO *DKIST* 4m solar observatory offers high spatial and temporal resolution observations of the solar photosphere and chromosphere (Rimmele et al., 2020, Sol. Phys., 295, 172).
- "*Cambridge Workshops of Cool Stars, Stellar Systems and the Sun*" conferences on related topics are held biennially (next meeting "CS24" will be in San Diego in 2024).
- *Cross-Divisional Synergy:* Observations of *Sun through Living With a Star* (LWS) Program of the NASA Heliophysics Division.
- *Note:* The observational and modeling research on the Sun and stars for gap SCI-15 has a connection to the needs for gap SCI-08 (understanding and mitigating stellar jitter for disk-unresolved stellar spectra for precise radial velocity and astrometric measurements). There may be synergies between approaches.

2.16. SCI-16: Complete the inventory of remotely observable exoplanet biosignatures and their false positives

- Connects to Astro2020 Decadal Science Panel Questions E-Q2, E-Q3, E-Q4
- Connects to PSA2022 Decadal Science Questions 12.9, 12.11
- *Related Gaps: SCI-02 (Modeling Exoplanet Atmospheres)*

Gap Summary:
Understanding observable biosignatures for potentially habitable planets is important to inform modeling of JWST spectroscopic surveys of transiting M dwarf exoEarths (preparatory work for enhancing JWST science return). While there has been significant advancement on the topic of biosignatures in recent years, there are frontier topics where further work would advance our ability to search for biosignatures, interpret them in the context of their environment, and strengthen their interpretation with regard to the search for life. This is precursor science as it may impact design choices for HWO on wavelength coverage, spectral resolution, or S/N requirements (to enable HWO to fulfill its Decadal mission goal "t*o search for biosignatures from a robust number of about ~25 habitable zone planets"*). Surveys for technosignatures present an opportunity to search for technological life and associated habitable worlds.

Capability Needed:
Wavelength limits of HWO (from UV through near-IR) and spectroscopy capability should factor in biosignatures, including the challenging case of whether high contrast UV observations of the ozone feature near ~0.25 μm in exoplanet spectra can be supported. Astro2020 (p. 4-9) states "*theoretical calculations of planetary atmosphere chemistry and evolution will be needed to interpret biosignature gases detected in exoplanet spectra. This theoretical research lays the groundwork for designing new observational programs and planning for new facilities*." *An Astrobiology Strategy for the Search for Life in the Universe* (2018) NAS report (Ch. 4) and *Astro2020* identify several frontier topics for biosignatures. The NAS *Astrobiology* report recommended that NASA "*should support research on novel and/or agnostic biosignatures*," "*direct the community's focus to address important gaps in understanding the breadth, probability, and distinguishing environmental contexts of abiotic phenomena that mimic biosignatures*," "*NASA should support expanding biosignature research to addressing gaps in understanding biosignature preservation and the breadth of possible positives and false negatives signatures,"* "*NASA should support the community in developing a comprehensive framework for assessment - including the potential for abiosignatures, false positives, and false negatives - to guide testing and evaluation of in situ and remote biosignatures*." *Biosignature* frontier topics listed both by Astro2020 (Sec. E) and 2018 Astrobiology Strategy NAS report include characterizing novel biosignatures, agnostic biosignatures, planetary processes that can change or mimic biosignatures, and develop statistical frameworks for assessing biosignatures taking into account system observables (to assess confidence that potential biosignatures might be due to life). As Earth was habitable for billions of years early in its history, but oxygen poor (with correspondingly weak O_2 and O_3), biosignatures for worlds analogous to Proterozoic and Archean Earth are of particular interest.

Capability Today:

- "*Community Report from the Biosignatures Standards of Evidence Workshop*" from NfoLD/NExSS Standards of Evidence for Life Detection Community Workshop (2021)
- The state of the biosignatures field is reviewed in Ch. 4 of the NAS report and the series of papers in the June 2018 issue of Astrobiology.
- JWST transit spectroscopy observations of transiting temperate rocky exoplanets orbiting M dwarfs (e.g., TRAPPIST-1).
- Modeling of individual target systems (e.g., TRAPPIST-1 planets, Proxima Cen b).
- Survey of potential biosignature gases by Seager, Bains, and Petkowski (2016, Astrobiology 16 465).
- HabEx and LUVOIR studies presented detailed science cases for searching for biosignatures and confirming habitability (e.g., LUVOIR Signature Science Case #2) and incorporated it into their strategies for the search for Life.
- *Technosignatures*: 2018 Technosignatures (TS) Workshop presented the status of technosignatures searches and future opportunities. 2020 Technoclimes Workshop (Haqq-Misra et al., 2022, Acta Astronautica, 198, 194) summarized future theoretical and observational studies on TS and science cases for future missions.

Mitigations in Progress:

- NASA ROSES ICAR opportunities are supporting multiple projects aimed at identifying habitable exoplanet targets or modeling exoplanet biosignatures.
- Community workshops: Oxygen in Planetary Biospheres (Green Bank Blumberg Astrobiology Workshop 2023), 2nd Annual Penn State SETI Symposium (2023)
- Sagan Summer Workshop 2023 theme is "*Characterizing Exoplanet Atmospheres: The Next Twenty Years*" and includes topics of biosignatures and technosignatures.
- Following up on the 2018 Technosignatures Workshop, ExEP is supporting a technosignatures gap study to survey the field and catalog approaches in a systematic manner.
- The 2022 NASA ROSES Astrophysics Decadal Survey Precursor Science opportunity solicited research in areas related to the Astro2020-recommended large missions where investigations can reduce design and development risk or define requirements. The topic was called out in Precursor Science gap list as gap "*#1 Modeling Exoplanet Atmospheres and Biosignatures.*"
- *Cross-Divisional Synergy:* NASA Astrobiology program and its Research Coordination Networks (RCNs): Nexus for Exoplanet System Science (NExSS), Network for Life Detection (NfoLD), Prebiotic Chemistry and Early Earth Environments (PCE3), Network for Ocean Worlds. NASA ROSES element C.4 Habitable Worlds supports research on using "*knowledge of the history of the Earth and the life upon it as a guide for determining the processes and conditions that create and maintain habitable environments*." ROSES element C.5 Exobiology supports research on "*the origin and early evolution of life, the potential of life to adapt to different environments, and the implications for life elsewhere*," with one of the emphases on "*Biosignatures and Life Elsewhere*."

3. Appendix of Common Acronyms for NASA ExEP

A&A	Astronomy & Astrophysics
AJ	Astronomical Journal
ALMA	Atacama Large Millimeter Array (observatory in Chile)
AO	Adaptive Optics
APD	Astrophysics Division
APF	Automated Planet Finder (robotic 2.4-m optical telescope at Lick Observatory)
ApJ	Astrophysical Journal
ApJS	Astrophysical Journal Supplement Series
ARC	Ames Research Center
ARIEL	Atmospheric Remote-sensing Infrared Exoplanet Large-survey (approved ESA M4 mission targeting 2029 launch)
au	Astronomical Unit (symbol is “au” per IAU 2012 Resolution B2)
CGI	Coronagraph Instrument (on Roman Space Telescope)
CHARA	Center for High Angular Resolution Astronomy
CHIRON	CTIO HIgh ResolutiON spectrometer (instrument on CTIO/SMARTS 1.5-m telescope at Cerro Tololo Inter-American Observatory (CTIO), Chile)
CMAP	Center for Matter at Atomic Pressures
COPAG	Cosmic Origins Program Analysis Group (PAG supporting community coordination and analysis for NASA Cosmic Origins Program)
COR	Cosmic ORigins Program
CUTE	Colorado Ultraviolet Transit Experiment (CubeSat)
DKIST	Daniel K. Inouye Solar Telescope (NSF National Solar Observatory facility)
DR	Data Release
DSCOVR	Deep Space Climate ObserVatoRy
EC	Executive Committee
EEID	Earth Equivalent Insolation Distance (EEID; $a_{EEID} = \sqrt{L}$ au where L is stellar luminosity in solar units, au is astronomical unit)
ELT	Extremely Large Telescope
EPOS	Exoplanet Population Observation Simulator
EPRV	Extreme Precision Radial Velocity
ERS	Early Release Science (JWST program)
ESA	European Space Agency
ESO	European Southern Observatory
ESPRESSO	Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (instrument for ESO VLT observatory)
ESS	Exoplanet Science Strategy (2018) National Academies Report
EUV	Extreme Ultraviolet
ExEP	Exoplanet Exploration Program
Exo-C	Exo-Coronagraph (2015 NASA Probe Mission Study)
ExoMol	*Mol*ecular line lists for *Exo*planet and other hot atmospheres (database)
Exo-S	Exo-Starshade (2015 NASA Probe Mission Study)
ExoPAG	Exoplanet Program Analysis Group (PAG supporting community coordination and analysis for NASA Exoplanet Exploration Program)
ExoSIMS	Exoplanet Open-Source Imaging Mission Simulator

EXPRES	Extreme PREcision Spectrometer (instrument on Lowell Discovery Telescope)
ExSDET	Exoplanet Standard Definitions and Evaluation Team
FFI	Full Frame Images
FGK	Stellar spectral types "F", "G", "K" – bracketing stars with "Sun-like" temperatures between about 3900-7200 Kelvin (Sun is G2 with T_{eff} = 5772K)
FUV	Far UltraViolet
GALAH	GALactic Archaeology with HERMES
GCM	General Circulation Model
GI	Guest Investigator
GOMAP	Great Observatories Mission and Technology MAturation Program
GPI	Gemini Planet Imager (instrument built for Gemini South 8.1-m telescope)
GSFC	Goddard Space Flight Center
GTO	Guaranteed Time Observations
HabEx	Habitable Exoplanet Imaging Mission (pre-Astro2020 concept study)
HARPS	High Accuracy Radial velocity Planet Searcher (instrument on ESO 3.6-m telescope at La Silla)
HARPS-N	High Accuracy Radial velocity Planet Searcher-North (instrument on Telescopio Nazionale Galileo 3.6-m telescope, La Palma, Canary Islands, Spain)
HATNet	Hungarian-made Automated Telescope Network
HD	Henry Draper (star catalog)
HERMES	High Efficiency and Resolution Multi-Element Spectrograph (instrument on Anglo-Australian Telescope)
HIRES	High Resolution Echelle Spectrometer (instrument for W. M. Keck Observatory)
HITEMP	High-TEMPerature molecular spectroscopic database
HITRAN	HIgh-resolution TRANsmission molecular absorption database
HOSTS	Hunt for Observable Signatures of Terrestrial Planetary Systems
HRCam	High-Resolution Camera (speckle instrument on SOAR 4.1-m telescope)
HRD	Hertzsprung-Russell Diagram
HST	Hubble Space Telescope
HWO	Habitable Worlds Observatory
HZ	Habitable Zone
ICAR	Interdisciplinary Consortia for Astrobiology Research
IR	Infrared
IROUV	InfraRed Optical UltraViolet space telescope (obsolete temporary name for Habitable Worlds Observatory)
IRTF	NASA Infrared Telescope Facility
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KELT	Kilodegree Extremely Little Telescope
KPF	Keck Planet Finder (radial velocity instrument for W. M. Keck Observatory)
JATIS	Journal of Astronomical Telescopes, Instruments, and Systems
JGRP	Journal of Geophysical Research: Planets
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KOI	Kepler Object of Interest
LAMOST	Large Sky Area Multi-Object Fibre Spectroscopic Telescope

LBT	Large Binocular Telescope
LBTI	Large Binocular Telescope Interferometer
LCOGT	Las Cumbres Observatory Global Telescope Network
LDT	Lowell Discovery Telescope (formerly Discovery Channel Telescope or DCT)
LUVOIR	Large UV/Optical/IR Surveyor (pre-Astro2020 concept study)
LWS	Living With a Star (NASA Heliophysics program)
MAROON-X	Magellan Advanced Radial velocity Observer of Neighboring eXoplanets (instrument on Gemini-North telescope)
MINERVA-Australis	Miniature Exoplanet Radial Velocity Array – Australis (observatory at Mt. Kent Observatory, Queensland, Australia)
MNRAS	Monthly Notices of the Royal Astronomical Society
MSFC	Marshall Space Flight Center
NACO	Nasmyth Adaptive Optics System (instrument for VLT observatory)
NAI	NASA Astrobiology Institute
NASA	National Aeronautics and Space Administration
NEID	NN-Explore Exoplanet Investigations with Doppler spectroscopy (pronounced ‘*noo-id*’ – derived from the word meaning ‘to see’ in native language of the Tohono O’odham, on whose land Kitt Peak National Observatory is located)
NESSI	NASA Exoplanet Star (and) Speckle Imager (instrument for Palomar 5-m telescope)
NExScI	NASA Exoplanet Science Institute
NExSS	Nexus for Exoplanet System Science
NfoLD	Network for Life Detection (NASA Research Coordination Network)
NIRC2	Near InfraRed Camera 2 (instrument for W.M. Keck Observatory)
NN-EXPLORE	NASA-NSF EXoPLanet Observational Research
NOIRLab	National Optical-Infrared Astronomy Research Laboratory (NSF center)
NPOI	Navy Precision Optical Interferometer
NSF	National Science Foundation
NUV	Near UltraViolet
PAG	Program Analysis Group (generic term for ExoPAG, PhysPAG, COPAG)
PASP	Publications of the Astronomical Society of the Pacific
PDR	Preliminary Design Review
PEAS	Planet as Exoplanet Analog Spectrograph
PFS	Carnegie Planetary Finder Spectrograph (instrument on Magellan II 6.5-m telescope)
PhysCOS	Physics of the Cosmos Program
PhysPAG	PhysCOS Program Analysis Group (PAG supporting community coordination and analysis for NASA Physics of the Cosmos Program)
PRV	Precision Radial Velocity
PSD	Planetary Science Division
PTF	Palomar Transient Factory
RCN	Research Coordination Network
Robo-AO	Robotic-Adaptic Optics (instrument now on U. Hawai’i 2.2-m telescope)
ROSES	Research Opportunities in Space and Earth Science

RV	Radial Velocity
SAG	Science Analysis Group
SDO	Solar Dynamics Observatory
SGL	Science Gap List
SIG	Science Interest Group
SIT	Science Investigation Team
SMARTS	Small & Moderate Aperture Research Telescope System (consortium operating telescopes on Cerro Tololo, Chile, including CTIO/SMARTS 1.5-m telescope)
SMD	Science Mission Directorate
SMP	Single Measurement Precision
SOA	State Of the Art
SOAR	SOuthern Astrophysical Research (4.1-m telescope at Cerro Pachon, Chile)
SPA	Science Plan Appendix
SPARCS	Star-Planet Activity Research CubeSat
SPHERE	Spectro-Polarimetric High-contrast Exoplanet REsearch (instrument on VLT)
SPIE	Society of Photo-Optical Instrumentation Engineers
START	Science, Technology, Architecture Review Team (new group starting in 2023 to guide GOMAP activities for HWO)
STDT	Science and Technology Definition Team
TBD	To Be Determined
TESS	Transiting Exoplanet Survey Satellite
TheoReTS	Theoretical Reims-Tomsk Spectral data (database)
TIC	TESS Input Catalog
TOI	TESS Object of Interest
TPF	Terrestrial Planet Finder (name used from 1999-2010 for future exoplanet direct imaging mission)
TRAPPIST	Transiting Planets and Planetesimals Small Telescope
TTV	Transit Timing Variations
UV	UltraViolet
VLT	Very Large Telescope
VLTI	Very Large Telescope Interferometer
WASP	Wide Angle Search for Planets
WG	Working Group
WIYN	Wisconsin, Indiana, Yale, NOAO Observatory
WFIRST	Wide-Field Infrared Survey Telescope (previous name for Nancy Grace Roman Space Telescope or Roman Space Telescope for short)
XRP	eXoplanet Research Program (an element of the NASA Research Opportunities in Space and Earth Sciences (ROSES) program)
XUV	classically “XUV” in laboratory studies and heliophysics often refers to “Extreme Ultraviolet,” more commonly acronymed as “EUV” in astronomy, however in recent exoplanet and stellar astronomy literature “XUV” refers to *combined X-ray and extreme ultraviolet* flux, covering the wavelength range of stellar emission important for photodissociation and ionization in planetary atmospheres.

4. Adopted Exoplanet Terms

A few practical definitions have been adopted for the ExEP Science Gap List which follow guidance from the Astro2020 Decadal Survey and recent influential studies. These are not meant to be exhaustive summaries on these terms, but to provide background on the programmatic use of these terms and point the reader to relevant literature.

4.1. “Habitable Zone”

“Habitable zone” **(HZ)** defines a region around a star where the surfaces of some planets may be able to support liquid surface water. When otherwise not specified, it corresponds to orbital radii of 0.95-1.67 au for the Sun (Astro 2020 p. 7-16), and for other stars scales as the square root of the bolometric luminosity normalized to the Sun’s (L/L_{Sun} ; Kopparapu et al., 2013, ApJ, 765, 131; LUVOIR Report p. B-13). Although these limits are called the “***optimistic habitable zone***” in Astro2020, their origin is the “***conservative habitable zone***” from Kasting et al. (1993, Icarus, 101, 108), corresponding to the “*water-loss*” and “*maximum greenhouse*” limits. Kopparapu et al. (2013) derived updated, but similar, limits from newer models, however they recommend that the original 0.95-1.67 au limits “*should be used for current RV surveys and Kepler mission to obtain a lower limit on eta-Earth so that future flagship missions like TPF-C and Darwin are not undersized*.” The LUVOIR and HabEx studies both adopted the 0.95-1.67 au limits and scaled with bolometric luminosity, and this was adopted by Astro2020. The limits of the habitable zone for varying assumptions about the atmospheric composition, water content, rotation, etc. may vary widely, and this definition used here is meant to provide a fiducial definition to guide mission studies.

4.2. “Earth-sized”

Astro2020 (p. 2-12, Fig. 7.6, p. 7-16) adopted the exoplanet description ***“Earth-sized”*** to correspond to radii of 0.8-1.4 Earth radii. 1 R_{Earth} = “Earth radius” = IAU nominal terrestrial radius = 6378.1 km. However the LUVOIR and HabEx concept studies allowed for smaller planets with lower radius limit of $0.8(a^*(L/L_{Sun})^{0.5})^{-0.5}$ (Kopparapu et al., 2018, ApJ, 856, 122), where a is the orbital semi-major axis in au, L is the stellar bolometric luminosity, L_{Sun} is the IAU nominal solar bolometric luminosity (3.828e26 W). The lower radius limit corresponds approximately to the “*cosmic shoreline*” where planets above that radius appear to retain their atmospheres, based on an empirical relation between insolation flux and escape velocity (Zahnle & Catling 2017, ApJ, 843, 122). The upper limit of 1.4 R_{Earth} corresponds to the observed limit transition between rocky and gaseous planets (e.g., Rogers 2015, ApJ, 801, 41). Note that for mass-radius relations appropriate for planets of Earth-like composition ($R/R_{\mathrm{Earth}} \cong (M/M_{\mathrm{Earth}})^{1/3.7}$; Zeng et al. 2016, ApJ, 819, 127), radii limits of 0.8 R_{Earth} and 1.4 R_{Earth} correspond to approximately 0.4 to 3.5 M_{Earth}. For a star of the Sun’s luminosity, the “*cosmic shoreline*” lower radius limit ranges from 0.82 R_{Earth} at the inner HZ edge (0.95 au) to 0.62 R_{Earth} at the outer HZ edge (1.67 au). For the Earth-like composition mass-radius relation, these radii correspond to approximate lower masses of 0.48 M_{Earth} and 0.17 M_{Earth}, respectively.

4.3. “Potentially Habitable Worlds/Planets/Exoplanets”

“Potentially habitable worlds/planets/exoplanets” (Astro2020, pgs. 2-12, 7-16, Fig. 7-6; Exoplanet Science Strategy, pgs. S-2, S-4, 2-3), “***ExoEarth candidates***”, (Astro 2020, p. I-2; Kopparapu et al. 2018, ApJ, 856, 122) or “***exo-Earth candidates***” (HabEx report 2019) are then defined to be *“Earth-sized” planets in the “habitable zone”* (following the previous stated constraints in size and orbital semi-major axis). Indeed Astro2020 Fig. 7.6 assumed a 2-parameter definition - “*Habitable zone is defined as 0.95-1.67 AU for planets of 0.8-1.4 Earth radii*” - as their metric for comparing yields as function of telescope diameter for different telescope architectures. The Exoplanet Science Strategy (2018) also generically referred to these planets as “***temperate terrestrial/rocky planets***” (ESS 2018, p. S-2, S-3). The terms are used in the Astro2020 Decadal Survey and Exoplanet Science Strategy (2018) to apply to such planets whether they orbit solar-type stars (e.g., FGK dwarfs) or M dwarfs. These terms are ***not*** meant to imply that a given planet has life or that it is exactly, or even closely, Earth-like in any parameter besides size and instellation or orbital radius (e.g., atmosphere, ocean, tectonics, life, etc.) – *it merely defines a two parameter search space (e.g., planet size and orbital radius) to focus the observational search for signs of habitability (i.e., liquid surface water) and life (i.e., biosignatures) on exoplanets*. The definition has, and will continue to have, *programmatic* importance to NASA ExEP as it is used to define metrics for science yields for comparing mission concept options, in support of the Astro2020 Decadal goal to “*realize a mission to search for biosignatures from a robust number of about ~25 habitable zone planets*” and “*provide a robust sample of ~25 atmospheric spectra of potentially habitable exoplanets*.”