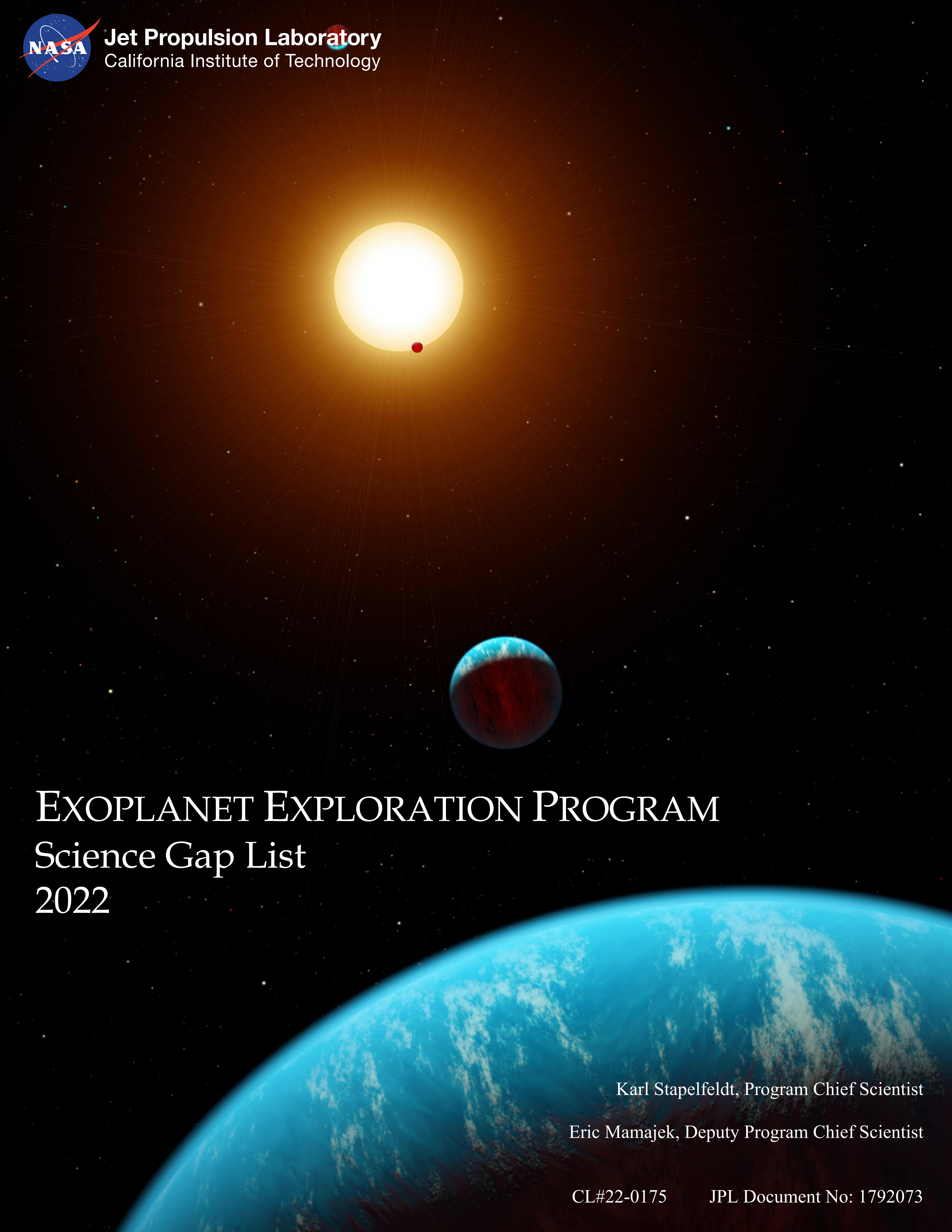

Jet Propulsion Laboratory
California Institute of Technology

Exoplanet Exploration Program

Science Gap List

2022

Karl Stapelfeldt, Program Chief Scientist

Eric Mamajek, Deputy Program Chief Scientist

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Cover Art Credit: NASA/JPL-Caltech. Artist conception of the K2-138 exoplanetary system, the first multi-planet system ever discovered by citizen scientists[1]. K2-138 is an orangish (K1) main sequence star about 200 parsecs away, with five known planets all between the size of Earth and Neptune orbiting in a very compact architecture. The planet's orbits form an unbroken chain of 3:2 resonances, with orbital periods ranging from 2.3 and 12.8 days, orbiting the star between 0.03 and 0.10 AU. The limb of the hot sub-Neptunian world K2-138 f looms in the foreground at the bottom, with close neighbor K2-138 e visible (center) and the innermost planet K2-138 b transiting its star. The discovery study of the K2-138 system was led by Jessie Christiansen and collaborators (2018, Astronomical Journal, Volume 155, article 57).

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

This document has been cleared for public release (CL#22-0175).

[1] https://www.jpl.nasa.gov/spaceimages/details.php?id=PIA22088

Approved by:

E-SIGNED by Gary Blackwood on 2022-01-21 16:36:55 GMT	2022-01-21 16:36:55 UTC
Dr. Gary Blackwood Program Manager Exoplanet Exploration Program Office NASA/Jet Propulsion Laboratory California Institute of Technology	Date
E-SIGNED by Douglas Hudgins on 2022-01-18 14:10:44 GMT	2022-01-18 14:10:44 UTC
Dr. Douglas Hudgins Program Scientist Exoplanet Exploration Program Science Mission Directorate NASA Headquarters	Date
E-SIGNED by Hannah Jang-Condell on 2022-01-21 18:08:05 GMT	2022-01-21 18:08:05 UTC
Dr. Hannah Jang-Condell Deputy Program Scientist Exoplanet Exploration Program Science Mission Directorate NASA Headquarters	Date

Created by:

E-SIGNED by Karl Stapelfeldt on 2022-01-18 20:10:46 GMT	2022-01-18 20:10:46 UTC
Dr. Karl Stapelfeldt Chief Program Scientist Exoplanet Exploration Program Office NASA/Jet Propulsion Laboratory California Institute of Technology	Date
E-SIGNED by Eric Mamajek on 2022-01-14 00:58:18 GMT	2022-01-14 00:58:18 UTC
Dr. Eric Mamajek Deputy Program Chief Scientist Exoplanet Exploration Program Office NASA/Jet Propulsion Laboratory California Institute of Technology	Date

The 2022 Exoplanet Exploration Program (ExEP) Science Gap List

Compiled and maintained by:
Dr. Karl Stapelfeldt, Program Chief Scientist
Dr. Eric Mamajek, Deputy Program Chief Scientist
NASA Exoplanet Exploration Program Office
Jet Propulsion Laboratory, California Institute of Technology

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 goal to "*Discover and study planets around other stars, and explore whether they could harbor life*." ExEP's three aims are:

- *discovering planets around other stars,*
- *characterizing their properties, and*
- *identifying 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*[2] 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.

[2] Much of this preamble text is drawn from the longer introduction to the ExEP Science Plan Appendix (SPA), which provides further context for the ExEP Science Plan.

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 science return of current and future NASA exoplanet missions.*

Making the gap list public signals to the broader community where focused science investigations are needed over the next 3-5 years in support of ExEP goals. The ExEP Science Gap List represents activities and investigations that will advance the goals of NASA's Exoplanet Exploration Program, and provides brief summaries in a convenient tabular format. 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 as needed approximately every two years. Entries in the *Science Gap List* will map to sections of the *Science Plan Appendix*.

The most recent community report relevant to the NASA ExEP is the *Pathways to Discovery in Astronomy and Astrophysics for the 2020s* (*Astro2020*) Decadal survey report[3] 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)[4] and *An Astrobiology Strategy for the Search for Life in the Universe*[5], 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*" call 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"

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3 https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020

4 https://www.nap.edu/catalog/25187/exoplanet-science-strategy

5 https://www.nap.edu/catalog/25252/an-astrobiology-strategy-for-the-search-for-life-in-the-universe

(EPRV-WG), which developed and presented a blueprint for a strategic EPRV initiative to NASA and NSF in March 2020[6], and produced a final report in summer 2021[7].

The 2018 Exoplanet Science Strategy report provided "*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*

- *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 ESS also provided seven recommendations and thirty five findings. The ESS goals, recommendations, and findings are summarized in Appendix B of the *ExEP Science Plan Appendix*.

The *Astro2020* Decadal Survey was released only weeks before the editing window closed for the 2022 update for the ExEP Science Gap List. The NASA Astrophysics Division and Exoplanet Exploration Program are actively considering their responses to *Astro2020*. So while the recommendations from the 2018 *Exoplanet Science Strategy* and *An Astrobiology Strategy for the Search for Life in the Universe* reports are factored into the *2022 ExEP Science Gap List*, we only acknowledge 1) that the *Astro2020* Decadal Survey was released, and 2) that it's "*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 ($\sim10^{-10}$) imaging and spectroscopy. 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*", and hence the *2022 ExEP Science Gap List* is already reasonably well-aligned with the anticipated science needs for the new *Astro2020* recommendations in that regard. The next update (2023) will benefit from further community feedback and deliberation on the anticipated needs to address the scientific goals of the *Astro2020* Decadal Survey.

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 as a measuring stick when evaluating possible new program activities: if a proposed activity could close a gap, it would be considered for greater

6 https://exoplanets.nasa.gov/exep/NNExplore/EPRV/
7 https://exoplanets.nasa.gov/internal_resources/2000/

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 Survey, 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 judgements 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 pre-phase A studies, may appear in the SGL.

Appendix A provides a table of the acronyms encountered among the SGL descriptions.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-01	**Spectroscopic observations of the atmospheres of small exoplanets** *See SPA section 6 (atmospheres & biosignatures)*	The study of planetary atmospheres advances our knowledge of planetary formation and evolution. Large Near-IR/Optical/ UV space telescope recommended by Astro2020 will image and spectrally characterize exoplanets, with the goal to spectrally characterize (UV/vis/near-IR) 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.	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. Need targets that provide the most photons (orbiting nearby, brightest stars for their class). *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).	A handful of small exoplanets have been identified by RV and transit surveys and 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 ~100 new, small, mostly hot exoplanets suitable for spectroscopic followup. So far there are no imaging detections of small exoplanets. *Cross-Divisional Synergy:* 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).	There are approved JWST Cycle 1 and GTO observations to spectrally characterize a dozen small transiting exoplanets. High dispersion spectroscopy coupled with extreme AO coronagraphy is being developed and may provide some detections of hot planets smaller than Neptune. The Roman/CGI instrument may be able to spectrally characterize atmospheres of small exoplanets in the Tau Ceti system. LUVOIR and HabEx Astro2020 mission concept studies provide input on capabilities for Decadal Large Near-IR/Optical/UV telescope for studying the atmospheres of small exoplanets via direct imaging. *Cross-Divisional Synergy:* PEAS (Planet as Exoplanet Analog Spectrograph; Martin et al. 2020 Proc. SPIE 11447) will observe solar system planets as exoplanets.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-02	**Modeling exoplanet atmospheres** *See SPA section 6 (atmospheres & biosignatures)*	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.	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 with exospheres, lithospheres, hydrospheres, and potentially biospheres affect the observed properties of the atmosphere today and over the planet's history. Challenges include determining composition and properties of aerosols, understanding chemistry (e.g., reaction rates, photochemistry, mixing, etc., especially those relevant to producing biosignature false positives), radiative transfer modeling (including scattering prescriptions), 3D atmosphere dynamics (e.g., general circulation models), and high-fidelity simulations of instrumental effects on the observed spectra. Modeling of the effects of greenhouse gases for assessment of surface temperatures and stability of surface water (habitability). *Note*: Laboratory measurements of key molecular and aerosol opacities in relevant physical conditions is covered under gap SCI-13. Exoplanet interior structure and material properties is covered under gap SCI-14.	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 nonuniform 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). Series of papers on biosignatures papers in June 2018 issue of Astrobiology. Modeling of individual target systems (e.g., TRAPPIST-1 planets, Proxima Cen b).	Ongoing research by the community. ExoPAG SAG-10 (Cowan et al. 2015, PASP, 127, 311) quantified the needs and expected results from transit spectroscopy. *Cross-Divisional Synergies:* 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. NASA Astrobiology Program's Interdisciplinary Consortia for Astrobiology Research (ICAR) and its NExSS research coordination network foster research on aspects of exoplanet atmospheres and climate relevant to life and the detection and interpretation of biosignatures. NASA Planetary Science Division's Exobiology ROSES program to understand the origin, evolution, distribution, and future of life in the universe, including research on biosignatures relevant to spectroscopy of potentially habitable worlds.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-03	**Spectral signature retrieval** *See SPA section 6 (atmospheres & biosignatures)*	Systematic instrumental and stellar effects in timeseries photometry and high contrast images limit the ability to extract reliable exoplanet spectra amidst backgrounds of residual stellar signals. Key physical parameters such as spectral slopes and molecular abundances can be uncertain, and achieved spectral sensitivity may be worse than the photon noise limit. Early spectral detections have not withstood reanalysis (e.g., Deming & Seager 2017, JGRP, 122, 53).	Ability to reliably extract physical parameters, such as the atmospheric pressure-temperature profile and abundances of major atmospheric constituents. Quantify effects of planet mass and radius uncertainties on the derived atmospheric parameters. 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.	Community analyses of HST & Spitzer transit spectra and of imaging spectra from e.g., GPI & SPHERE. Simple noise models predict JWST transit spectra and coronagraphic spectra. Development of best practices over time to acquire 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 (e.g., Rackham et al. 2018, ApJ, 122, 853), 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 have conducted community data challenges for coronagraphic imaging. ExoPAG SAG 19 report defined new approaches to detection significance in high contrast imaging datasets.	The JWST Early Release Science Team for transit spectroscopy held a pre-launch data hackathon in June 2021, and will hold a data challenge on simulated transit data sets two months after the JWST launch (early 2022). ExoPAG SAG 21 is investigating the effect of stellar contamination on space-based transmission spectroscopy, held a community symposium on this topic in March 2021, and will deliver a final report in early 2022.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
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)*	Measurements of distribution of planetary parameters (e.g., masses, radii, orbital elements) from various techniques are important both for constraining planet formation and evolution models, and for predicting science yields for future missions. Understand the effects of stellar multiplicity on planet formation, evolution, and demographics. The lack of integrated exoplanet population studies limits our understanding of exoplanet demographics over a wide range of masses and radii. Extrapolations to HZ demographics need to be on best basis (see SCI-05).	Integrated exoplanet demographic results from different methods (e.g. transit, direct imaging, RV, and microlensing surveys). Include effects of Kepler DR25, 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. Planet formation and population synthesis models that account for the observed demographics. Quantify the impact of stellar binarity on exoplanet frequency, as many potential direct imaging target stars are in multiple systems.	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 0.07-400 au. 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) examine transit, radial velocity, and direct imaging occurrence rate results to constrain a turnover in the distribution of giant planets to between 3-10 au. Improved stellar parameters from e.g., Gaia DR2, TIC, GALAH, APOGEE, LAMOST, etc. result in improved estimates for planet properties and are allowing searches for trends. Moe & Kratter (2021, MNRAS, 507, 3593) review constraints on exoplanet frequency as function of stellar binary separation.	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. Exoplanet Standard Definitions and Evaluation Team (ExSDET) investigating reconciliation of Kepler transit results (e.g., ExoPAG13) with radial velocity survey results. There is a large community effort to validate TESS exoplanet candidates. ExoPAG SIG 2 is monitoring available data on exoplanet occurrence rates, and working on 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. Roman Space Telescope microlensing survey will measure occurrence rates for the cold planet population. *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.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-05	**Occurrence rates and uncertainties for temperate rocky planets (eta-Earth $\eta_\oplus$)** *See SPA sections: 2 (exoplanet populations), 5 (properties of target stars)*	A critical parameter guiding the design of the Large Near-IR/Optical/ UV space telescope recommended by Astro2020, capable of spectrally characterizing habitable zone planets orbiting nearby stars, is eta-earth ($\eta_\oplus$). The occurrence rate of Earth-sized planets in the habitable zones of their stars $\eta_\oplus$ remains considerably uncertain, and better characterization of $\eta_\oplus$ will reduce uncertainty in estimated science yields (detection, spectroscopy) and reduce the risk for the designed mission to provide the robust number of ~25 spectrally characterized potentially habitable exoplanets called for by Astro2020. SCI-05 is the subset of SCI-04 focusing specifically on occurrence rates of Earth-sized planets in/near habitable zones. Measurements of trends in $\eta_\oplus$ as functions of stellar parameters like e.g. mass, multiplicity, metallicity, etc. would improve predictions of yield estimates.	Analysis of occurrence rates taking into account final Kepler products and improved stellar parameters, such that remaining uncertainties are dominated by intrinsic Kepler systematics. Current estimates rely on transit data (e.g., Kepler). Ideally the values would be constrained and cross-checked via other methods (e.g., PRV), and trends as a function of stellar properties (e.g., mass, multiplicity, etc.) would be explored to help with target prioritization. Improve knowledge of mass-radius relations to improve fidelity of comparison between transit and PRV surveys. Mission studies for Astro2020 adopted $\eta_\oplus = 0.24^{+0.46}_{-0.16}$ for yield calculations, informed by SAG 13 (factor of 3 systematic uncertainty). Analysis work that reduces uncertainty and biases in $\eta_\oplus$ would be beneficial to direct imaging mission concepts. Encourage observations which can confirm the existence of candidate temperate rocky planets in Kepler data upon which $\eta_\oplus$ critically relies. Encourage research on physical processes shaping the small planet population so that extrapolations can be done with more fidelity.	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 helped inform mission concept studies. 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.	The community is actively working on planet occurrence rate studies that incorporate final Kepler DR25 data and Gaia. ExoPAG SIG 2 (Exoplanet Demographics) is active, and NExScI hosted an Exoplanet Demographics conference in Nov 2020. *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).

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-06	**Yield estimation for exoplanet direct imaging missions** *See SPA section 2 (exoplanet populations)*	Quantitative non-advocate science yield comparisons made on a common basis are needed to facilitate architecture trades for Astro2020's Near-IR/Optical/UV mission, for both detections and spectral characterizations. Community agreement is needed on key astrophysical input assumptions (gaps SCI-05, SCI-11) and definitions of the exoplanet characterization metrics being used.	Capability within the NASA Exoplanet Exploration Program to produce science yield estimates for exoplanet direct imaging missions using a transparent public code implemented independent of mission architecture advocates, to support the Great Observatories Mission and Technology Maturation Program for Astro2020's Near-IR/Optical/UV 6-m telescope. Derive mission yields and uncertainties so that the ability of each architecture option to achieve the goal of characterizing ~25 temperate rocky exoplanets is understood, as well as the yields of other planet types. Improved treatment of observation scheduling and mission rule optimization, in the use of precursor observations in planning of imaging observations, and in modeling of planet signals.	Stark et al. (2019, JATIS, 024009) presented the number of habitable zone rocky planet characterizations as function of aperture size, telescope type, and astrophysical assumptions. ExEP Standards Definition and Evaluation Team (Morgan et al. 2019, https://exoplanets.nasa.gov/exep/studies/sdet/ and Proc SPIE 11117) compared the number exoplanet characterizations of several different mission architectures using multiple spectral characterization metrics. 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.	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.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-07	**Intrinsic properties of known exoplanet host stars** *See SPA section 5 (properties of target stars)*	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. *Improvement of knowledge of stellar radii is outlined separately in SCI-12.*	Improved observational constraints on exoplanet and host star properties are needed to help inform the modeling of exoplanet atmospheres and interpretation of exoplanet spectroscopy (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 EUV emission informs 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., HRD position, 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. See ExoPAG SAG 17 report for further discussion on observational needs re: stellar characterization for TESS candidates.	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 Archive. Hypatia Catalog Database compiles stellar chemical abundance data for thousands of stars including mission target stars and >1300 exoplanet host stars.	NASA Exoplanet Archive is actively compiling data on exoplanets and their host stars. ExoPAG SAG 22 has listed sets of stellar properties and data that should be obtained, catalogued, 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 2023 to monitor NUV and FUV emission (and variability) for M dwarfs of a wide range of ages. ESCAPE Explorer concept proposed to survey nearby stars in the extreme UV, probing flares and coronal mass ejections for 200 nearby FGKM stars, including ~40 exoplanet host stars, but was not selected for flight implementation. *Note*: 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).

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
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)*	Measurements of masses and orbits are crucial for characterizing exoplanets, and for modeling their spectra and bulk composition. Precision radial velocity (PRV) and astrometry are the primary methods for measuring masses of nearby exoplanets. PRV is currently the predominant means of dynamically measuring exoplanet masses, and stellar "jitter" dominates RV uncertainty budget. Stellar RV "jitter" in its various forms, and over a variety of timescales, is an ever-present source of noise for both PRV and astrometric methods. It is not known whether current limits to PRV can be overcome to detect temperate Earth-mass planets orbiting Sun-like stars. If technological gap of achieving sub-microarcsecond-level astrometry is achievable, and astrometric jitter could be modeled at sub-microarcsecond-level, then astrometry could provide an alternative method which could yield orbits and masses for rocky planets around nearby stars.	Earth orbiting at 1 AU induces RV semi-amplitude of only ~9 cm/s on the Sun, and Earth-mass planet in corresponding HZ around an M dwarf star like Proxima Centauri (0.1 M_{Sun}) induces a RV semi-amplitude of ~1 m/s (measurable; e.g., Anglada-Escude et al. 2016, Nature, 536, 437). 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. PRV datasets for the Sun 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*sin*i*, representing tens of % of nearby direct imaging targets is prohibitive with EPRV, and astrometry may be required. *Astrometry*: Exo-Earth orbiting 1 M_{Sun} star at 10 pc induces amplitude of ~0.3 microarcsec. Predicted astrometric amplitudes for 1 M_{Earth} planets at EEID for large direct imaging mission targets within 30 pc range are predominantly between 0.1-1 microarcsec. For Sun-like activity levels, astrometric jitter would be ~0.05 microarcsec – small, but not negligible (but higher for more active stars).	*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 EPRV4 workshop (March 2019). 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. 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.	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. ExoPAG SAG-8 (Plavchan et al. 2015; arXiv: 1503.01770) discussed effective use of the resources needed for confirming exoplanets. EXPRES and MAROON-X have recently come online. KPF (on Keck) has been funded by NSF and will be commissioned in 2022. In response to ESS (2018) recommendation, NASA and NSF chartered Extreme Precision Radial Velocity Initiative Working Group (EPRV WG), which published their report in 2021. NASA is supporting a new ROSES element "Extreme Precision Radial Velocity Foundation Science" supporting several two-year investigations to address the stellar variability challenges identified by the EPRV WG. *Cross-Divisional Synergy:* Observations of *Sun through Living With a Star* (LWS) Program of Heliophysics Division. E.g., measurements of Doppler shifts due to solar oscillations, high res measurements of magnetic fields, chromosphere, etc. with Solar Dynamics Observatory (SDO) to provide input for interpreting Sun-as-star solar Doppler spectroscopy data to advance EPRV methods. The potential synergy between solar surface velocity field studies and exoplanet EPRV measurements remains to be developed.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-08 (cont)	**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)*	Note: Technology needs for EPRV and astrometry are tracked separately in the ExEP Technology Gap List.	Develop capability to perform precision astrometry on nearby bright stars as precursor or followup for large direct imaging mission, as backup to PRV for detecting temperate rocky planets and measuring their masses and orbits.	Note: Technology needs for EPRV and astrometry are tracked separately in the ExEP Technology Gap List.	Develop capability to perform precision astrometry on nearby bright stars as precursor or followup for large direct imaging mission, as backup to PRV for detecting temperate rocky planets and measuring their masses and orbits.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
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)*	The majority of current exoplanet discoveries have been made via the transit method, e.g., 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.	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 K2 and TESS candidates with quick look low-precision RV screening for false positives (e.g., eclipsing binaries), then high precision to determine masses of the best candidates. TESS follow-up requires PRV observing time in N and S hemispheres, sufficient to cover the expected ~15k TESS candidates of which ~1,250 should be detected in the 2-min cadence data, with ~250 smaller than 2 R_{Earth} (Barclay et al. 2018, ApJS, 239, 2). 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.	TESS has achieved 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 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_{Earth}, V<14.5; 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 observing 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).	NASA-NSF Partnership for Exoplanet Observational Research (NN-EXPLORE). NASA supported construction of NEID instrument, which was delivered to WIYN in 2020, however commissioning and initial community access was slowed by COVID-19 closures. Community access started in late 2020B. NN-EXPLORE is supporting US community access to SMARTS 1.5-m CHIRON and MINERVA-Australis. NASA supports community access to Keck HIRES and will support access to the new Keck KPF instrument (starting 2022), which will include queue-based scheduling. Options for additional southern hemisphere community PRV access continue to be explored. TESS is applying for a second mission extension in the 2022 Senior Review.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-10	**Precursor observations of direct imaging targets** *See SPA sections: 3 (exoplanet dynamics); 5 (properties of target stars), 6 (atmospheres & biosignatures)*	Precursor observations benefit future exoplanet missions by 1) screening for confusing 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).	Refined target lists consistent with the scope of the Astro 2020 Decadal-recommended direct imaging mission. For those targets, assess the bound companion (stellar and substellar) detection limits provided by existing data (e.g. PRV, 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 precision RV observing programs in both N and S hemispheres (executed consistently over > 5 years), and conduct observations using other techniques which may feasibly detect small planets orbiting nearby target stars (including e.g. astrometry, and IR high-contrast 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.	Howard & Fulton (2016, PASP, 128, 4401) completed a RV analysis to search for bound companions for stars in the 2014 versions of WFIRST CGI, Exo-S, and Exo-C target lists using data from California planet search. A similar study for Southern target stars has not been done. 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 coming online in 2022. Wagner et al. (2021, Nature Comm. 12, 922) VLT/NEAR observations of Alpha 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.	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 Astro2020's prioritized Near-IR/Optical/UV 6-m telescope,will be posted to NExScI in early 2022**,** to encourage community observations and analysis of these systems. NEID GTO program on WIYN is surveying ~20% of 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. Laliotis et al. are completing an archival analysis of PRV data from 5 spectrographs for ~100 S hemisphere stars likely to be targets of Astro2020 Decadal's recommended Near-IR/Opt/UV telescope. ESA Gaia mission Data Releases 3 and 4 (release date not yet announced) are expected to reveal astrometric perturbations by faint stellar companions and giant exoplanets for thousands of stars, some of which could be targets for direct imaging. Many of the target stars have been searched for close stelar companions by optical speckle imaging.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-11	**Understanding the abundance and distribution of exozodiacal dust** *See SPA section 11 (exozodiacal dust)*	Exozodiacal dust is a noise source that compromises imaging and direct spectroscopy of small planets in and around the habitable zones of nearby stars. Substructure in the exozodi distribution may mimic the presence of an exoplanet and thus confuse searches made with smaller telescope apertures. To date, substructure in the distribution of habitable zone dust has been mapped only for the case of our own solar system.	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 future exoplanet direct imaging missions. Theoretical modeling of dust sources and transport into the habitable zone. 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 m 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 warm dust levels in habitable zones.	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 telescope apertures < 4-m if the exozodi level is > +1 from the LBTI median result. Further observational work that reduced the uncertainty in the median exozodi level would reduce the risk of marginal spectroscopic science return by future direct imaging missions.	The Astro2020 Decadal Survey was silent on whether additional investments in exozodi measurements should be a priority. Options for further observational work include: 1) The LBTI instrument team has studied possible upgrades that would increase the sensitivity of their instrument by a factor of 2-3. 2) Roman CGI scientists have submitted a paper quantifying the sensitivity their 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. 3) Current near-IR interferometers and upcoming ELTs will have capabilities to constrain warm exozodi levels and these are still being assessed. A new nulling interferometer under development for the VLTI "SCIFY" will provide high S/N detections of hot exozodiacal dust in the L band. NASA XRP is funding theoretical studies and observational efforts to connect various observables. *Cross-Divisional Synergy:* research on interplanetary dust grains, understanding source dust populations and distribution of dust in the solar system.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-12	**Measurements of accurate transiting planet radii** *See SPA sections: 2 (exoplanet populations), 5 (properties of target stars)*	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 is on-track to exceed the number of Kepler+K2 candidates, and thus needs a similar	Detailed observations are needed to derive accurate stellar radii, including high res spectroscopy and resolving stellar companions. 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. See ExoPAG SAG 17 report discussing resource needs for TESS follow-up to constrain stellar and exoplanetary radii.	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. 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 observations. Injection and recovery tests can place further quantitative constraints on companions. For improving knowledge of host star T_{eff}, metallicity, gravity: high-res. spectroscopy surveys (e.g., California-Kepler survey), lower res. Spectroscopy surveys (e.g., APOGEE & LAMOST), and community access to spectrographs for extracting stellar spectra (e.g., Keck HIRES, NEID, CHIRON, etc.).	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: SCI-12 is for improving knowledge of exoplanet radii (especially for deblending the contributions from stellar companions, both physical and unphysical), whereas SCI-07 focusses on improving knowledge of other stellar parameters to help inform the interpretation and modeling of exoplanet data (e.g., spectra).

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-12 (cont.)		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 SCI-07.			
ID	**Title**	**Summary**	**Capability Needed**	**Capability Today**	**Mitigation in Progress**
SCI-13	**Properties of atoms, molecules and aerosols in exoplanet atmospheres** *See SPA section 6 (atmospheres & biosignatures)*	Understanding and interpreting the full gamut of upcoming exoplanet spectra from JWST, Roman CGI, ARIEL/CASE, and the eventual large IR/Optical/UV 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 species. Together these properties shape our understanding of the chemistry and climate of exoplanet atmospheres.	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 reactions rate coefficients 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).	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.	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.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-14	**Exoplanet interior structure and material properties**	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.	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.).	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).	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.

APPENDIX A: ACRONYM LIST

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
ARIEL	Atmospheric Remote-sensing Infrared Exoplanet Large-survey (approved ESA M4 mission targeting 2029 launch)
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
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)
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
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
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 w/temperature 5772K)
FUV	Far UltraViolet
GALAH	GALactic Archaeology with HERMES

GCM	General Circulation Model
GI	Guest Investigator
GPI	Gemini Planet Imager (instrument built for Gemini South 8.1-m telescope)
GTO	Guaranteed Time Observations
HabEx	Habitable Exoplanet Imaging Mission
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
HZ	Habitable Zone
ICAR	Interdisciplinary Consortia for Astrobiology Research
IRTF	NASA Infrared Telescope Facility
JWST	James Webb Space Telescope
KELT	Kilodegree Extremely Little Telescope
KPF	Keck Planet Finder (future 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
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
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
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
PASP	Publications of the Astronomical Society of the Pacific
PEAS	Planet as Exoplanet Analog Spectrograph
PFS	Carnegie Planetary Finder Spectrograph (instrument on Magellan II 6.5-m telescope)
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
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
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	X-ray and Ultraviolet