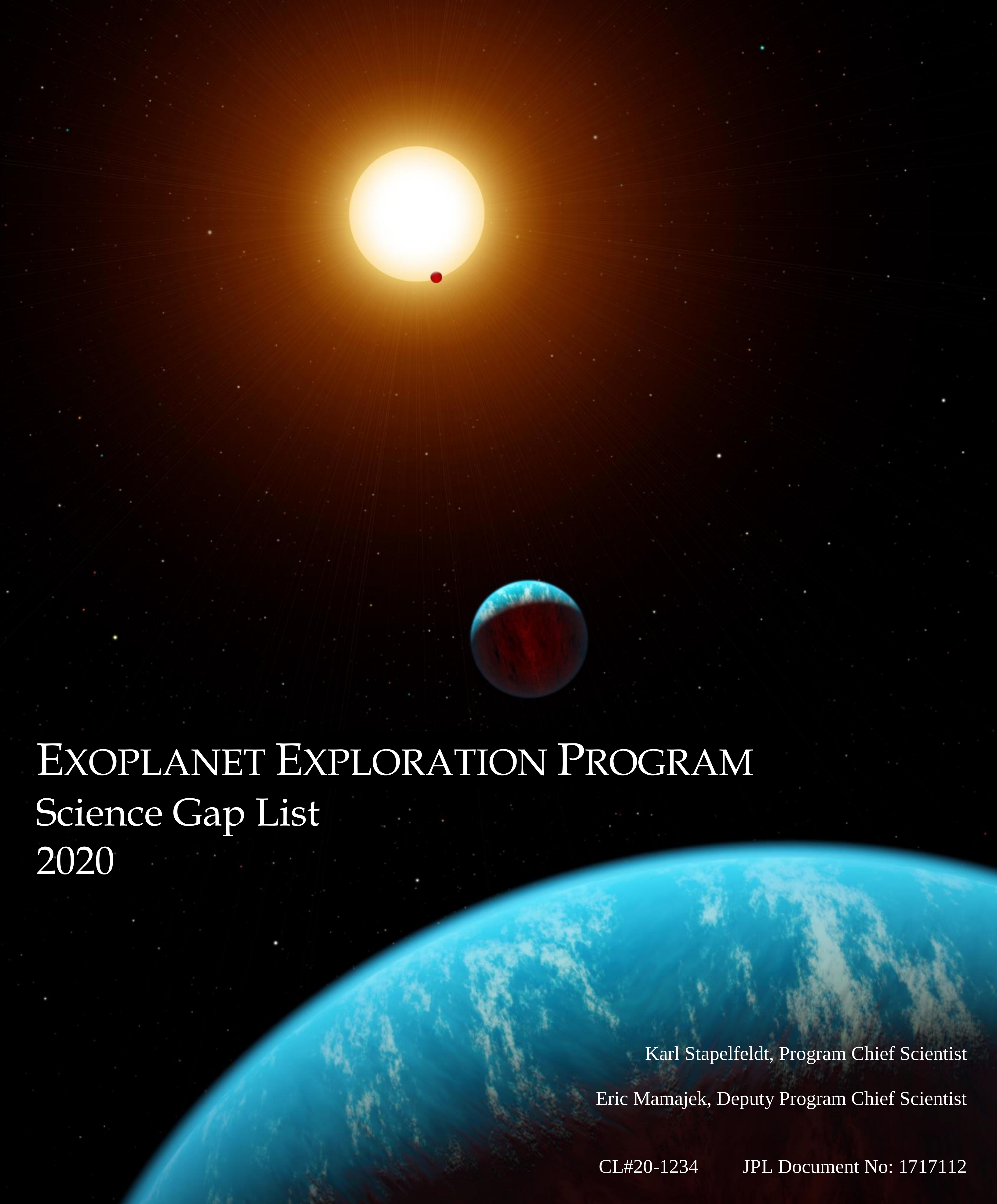
Jet Propulsion Laboratory
California Institute of Technology



EXOPLANET EXPLORATION PROGRAM

Science Gap List

2020

Karl Stapelfeldt, Program Chief Scientist

Eric Mamajek, Deputy Program Chief Scientist

CL#20-1234 JPL Document No: 1717112

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#19-0790).

---

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

Approved by:

E-SIGNED by Gary Blackwood
on 2020-02-27 05:37:57 GMT

2020-02-27 05:37:57 UTC

Dr. Gary Blackwood
Program Manager,
Exoplanet Exploration Program Office
NASA/Jet Propulsion Laboratory

Date

E-SIGNED by Douglas Hudgins
on 2020-03-04 19:20:38 GMT

2020-03-04 19:20:38 UTC

Dr. Douglas Hudgins
Program Scientist
Exoplanet Exploration Program
Science Mission Directorate
NASA Headquarters

Date

Created by:

E-SIGNED by Karl Stapelfeldt
on 2020-03-03 01:33:06 GMT

2020-03-03 01:33:06 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 2020-02-27 01:14:27 GMT

2020-02-27 01:14:27 UTC

Dr. Eric Mamajek
Deputy Program Chief Scientist
Exoplanet Exploration Program Office
NASA/Jet Propulsion Laboratory
California Institute of Technology

Date

The 2020 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
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 [4]:

- 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 will be https://exoplanets.nasa.gov/exep/science-overview/.

---

[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.

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 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 National Academies' *Exoplanet Science Strategy* (ESS) released in September 2018 [3]. The ESS report provides a broad-based community assessment of the state of the field of exoplanet science and recommendations for future investments. The National Academies also released the report *An Astrobiology Strategy for the Search for Life in the Universe* in October 2018. NASA HQ is considering responses to the *Exoplanet Science Strategy* and *Astrobiology Strategy* reports. One response has been the chartering of the "Extreme Precision Radial Velocity Working Group" (EPRV-WG), which will develop a blueprint for a strategic EPRV initiative to NASA and NSF in early 2020. The Astro2020 Decadal Survey is expected to strongly consider the recommendations of the ESS report, and their direction to NASA will guide priorities for the Astrophysics Division and Exoplanet Exploration Program.

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 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 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 evershifting 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.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-01	**Spectral characterization of atmospheres of small exoplanets** *See SPA section 6 (atmospheres & biosignatures)*	The study of planetary atmospheres advances our knowledge of planetary formation and evolution, and can provide chemical evidence for biological processes. There are few extant spectroscopic detections of atmospheres for exoplanets smaller than Neptune, even though they dominate the exoplanet population. The first constraints are being obtained for the atmospheric composition of small temperate planets (i.e. sub-Neptunes), but detection of definitive spectral features for temperate rocky planets is beyond the current capability. In order to remotely assess the frequency of habitable planets and life in the galaxy, new observations and facilities must be developed.	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, 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 spectroscopic observations (gap SCI-09), need for precursor surveys to find direct imaging targets (gap SCI-10).	A handful of small exoplanets suitable for spectroscopy have been identified by RV and transit surveys. HST transit spectra of these have marginal sensitivity and would only be able to detect cloud-free H-dominated atmospheres, which are not expected for this class of objects. So far there are no imaging detections of small exoplanets.	Current and future JWST proposals to spectrally characterize small transiting planets. Small transiting exoplanets discovered with K2, TESS, and ground-based transit surveys, can be observed with JWST. WFIRST/CGI may be able to spectrally characterize atmospheres of small planets orbiting the very nearest stars. Mission concept studies for Astro2020 have defined capabilities for next generation of observatories to study atmospheres of small exoplanets via transit spectroscopy (e.g. Origins, LUVOIR, HabEx) or direct imaging (e.g. LUVOIR, HabEx).

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, as a function of the total 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. Challenges include determining composition and properties of aerosols, understanding chemistry (e.g. reaction rates, photochemistry, mixing, etc.), radiative transfer modeling (including scattering prescriptions), 3D atmosphere dynamics (e.g. general circulation models). and high-fidelity simulations of	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 to spectral observations (e.g. HST, JWST, future missions, etc.). 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. NASA ROSES programs in the Planetary Sciences Division support fundamental research on planetary atmospheres, including their origin, evolution, and characterization. NASA Astrobiology Program is now the Interdisciplinary Consortia for Astrobiology Research (ICAR) including the NExSS research coordination network, designed to foster interdisciplinary research on aspects of exoplanet atmospheres and climate relevant to life and biosignatures.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
			instrumental effects on the observed spectra. Laboratory measurements of key molecular and aerosol opacities in relevant physical conditions.		
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 spectra from 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 atmospheric pressure-temperature profile and abundances. Thorough understanding of the limits of the data, including effects of correlated and systematic noise sources. Strategies for data taking, calibration, processing to mitigate these issues for each individual instrument/observatory and lessons learned for future work.	Community analyses of HST 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 JWST. Studies of contamination by stellar photospheric heterogeneities as 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 direct imaging spectra of exoplanets (e.g. Rizzo et al. 2018, SPIE, 10698).	WFIRST SITs performing retrieval experiments for CGI imaging spectra and community data challenges. ExoPAG SAG 19 Exoplanet Imaging Data Challenge for ground-based coronagraphy. Data challenges planned by JWST ERS team for transits.

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 popluations),* *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 yields of future missions. 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 transit, direct imaging, RV, and microlensing surveys. Include effects of Kepler DR25, the low yield of direct imaging detections of self-luminous planets, and microlensing results from recent campaigns. Update periodically to include new surveys such as TESS, and to correct the host star properties used in prior surveys. The effect of measurement uncertainties on the results must be quantified. There is a need for planet formation models which account for the observed demographics.	Ongoing microlensing, RV, transit, and direct imaging projects continue to build statistics. Examples: Clanton & Gaudi (2016, ApJ, 819, 125) for demographics of exoplanets on wide separation orbits (>2 AU) for M dwarfs. Pascucci et al. (2018) 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_J mass range for M dwarfs over 0.07-400 au. Exoplanet Population Observation Simulator (EPOS) compares synthetic planet population models to observations (e.g. Mulders et al. 2019, arXiv:1905.08804).	Ongoing community efforts for assessing occurrence rates for close-in planets with Kepler and K2 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 synthesizing available data on exoplanet occurrence rates. WFIRST microlensing survey is designed to measure occurrence rate of cold planet population.

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 popluations), 5 (properties of target stars)*	Subset of SCI-04 focusing on occurrence rates for Earth-sized planets in/near habitable zones, which remains considerably uncertain. Critical to NASA for designing a large direct imaging mission for detecting and characterizing Earth analogs around nearby stars. Reducing uncertainty in $\eta_\oplus$ reduces uncertainty in predicted yields for imaged and spectrally characterized temperate rocky planets.	Analysis of occurrence rates taking into account final Kepler data products (DR25), including effects of stellar multiplicity, and improved stellar parameters - such that the remaining uncertainties are dominated by intrinsic Kepler systematics. Mission studies for Astro2020 adopted $\eta_\oplus = 0.24^{+0.46}_{-0.16}$ for yield calculations, informed by SAG 13 analysis (factor of 3× systematic uncertainty). Analysis work that reduces uncertainty in $\eta_\oplus$ would be beneficial to direct imaging mission concepts.	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. 2019, arxiv: 1906.03575). 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.	This is an active research area. The community is working on planet occurrence rate studies that incorporate final Kepler DR25 data and Gaia. Encourage observations which can confirm existence of candidate temperate rocky planets in Kepler data upon which $\eta_\oplus$ critically relies.
SCI-06	**Yield estimation for exoplanet direct imaging missions** *See SPA section: 2 (exoplanet popluations)*	Quantified, non-advocate science yield comparisons made on a common basis between various mission concepts, for both detections and spectral characterizations. Community agreement on key astrophysical input assumptions.	Capability within NASA Exoplanet Program to provide peer review of yield estimates made by individual mission studies, using a transparent public code implemented independently, and available for future mission study trades.	Stark et al. (2019, JATIS, 024009) show yield as function of aperture size and astrophysical assumptions, however a number of idealized assumptions were used.	ExSDET completed its final report in fall 2019 using ExoSIMS package for exoplanet yield calculations, in coordination with members of concept study teams, and proceeding with visibility to stakeholders.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-07	**Properties of known exoplanet host stars** *See SPA section 5 (properties of target stars)*	Improvement of measurement of exoplanet parameters needed for interpreting spectra rely directly on improvement of fidelity of stellar parameters based on photometry, spectroscopy, astrometry, etc., and subsequent analysis. *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), including: high energy emission (e.g. UV, X-rays, flare properties), ages, precision stellar abundances for elements important to exoplanetary structure/formation/ evolution and biology. 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 stellar, substellar, or planetary companions is helpful for interpretation of exoplanet properties and modeling (e.g. dynamics).	NExScI 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.	NExScI Exoplanet Archive is actively compiling data on exoplanets and their host stars. ExEP plans to post compiled target list informed by direct imaging mission studies at NExScI in 2020. 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-08	**Mitigating stellar jitter as limitation to sensitivity of dynamical methods to detect 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 (see ESS report p. 4-30). PRV is currently the predominant means of dynamically measuring masses of exoplanets, and stellar jitter dominates RV uncertainty budget. Stellar RV "jitter" in its various forms (attenuation of convective blueshift by stellar magnetic activity, granulation, non-radial oscillations, etc.) is an ever-present source of noise over a variety of timescales for both PRV and astrometric methods. While PRV is capable of reaching Earth-mass planets in HZs around M dwarfs, it is not known whether current limits to PRV can be overcome to detect Earth-like planets orbiting solar-type (FGK) stars. If technological gap of achieving sub-μas-level astrometry is achievable, and astrometric jitter could be understood/modeled at	**PRV:** Earth orbiting at 1 AU around a G2V star has RV amplitude of ~9 cm/s, and Earth-mass planet in corresponding HZ around M2V star (~0.2 AU) has RV amplitude of ~30 cm/s. RV jitter intrinsic to star is at ~m/s level, and higher for active stars. 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 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 velocities for characterizing temperate rocky planets for stars hotter than ~F7, and/or with high *v*sin*i*, representing tens of % of nearby direct imaging	**PRV:** Smallest claimed RV amplitudes detected today are ~0.4 m/s for Tau Ceti. Modern single measurement precision (SMP) among ongoing RV surveys summarized in Fischer et al. (2016, PASP, 128, 066001): HARPS and HARPS-N leading the way with 0.8 m/s. NEID in development (~0.3 m/s). Instrument systematics and stellar noise are not well understood. SOA in PRV capabilities were presented at EPRV4 workshop (March 2019). **Astrometry:** Studies on stellar astrometric jitter of stars and the Sun from 2000s during development phases for SIM and Gaia. Existing ground-based astrometry (CHARA, NPOI, VLTI) cannot reach accuracy required. Gaia is collecting data that should lead to astrometric detections of giant exoplanets.	Major NASA investment in PRV instrument (NEID) for WIYN (northern hemisphere 4-m class). NEID data for RV standard stars will be made public immediately. Investigating options for archiving solar data with PRV spectrographs. SAG-8 (Plavchan, Latham et al. 2015; arXiv:1503.01770) discussed effective use of the resources needed for confirming exoplanets. Upon ESS recommendation, NASA and NSF chartered Extreme Precision Radial Velocity Initiative Working Group in 2019 to provide community blueprint for agency support of EPRV progress through 2020s (report to be delivered early 2020).

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-08 (cont.)		sub-μas-level, then astrometry could provide an alternative method which could yield orbits and masses for rocky planets around nearby stars. Note: technology needs for EPRV and astrometry are tracked separately in ExEP Technology Gap List.	targets, is even more challenging. **Astrometry:** Exo-Earth orbiting 1 M_{Sun} star at 10 pc induces amplitude of ~0.3 μas. 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 μas. For Sun-like activity levels, astrometric jitter would be ~0.05 μas – small, but not negligible (but higher for more active stars). 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)*	Exoplanet candidates detected via various methods require confirmation and measurement of masses (the majority discovered presently and in near future will be via transit method, e.g. K2, TESS). Mass constraints are crucial for understanding atmospheric spectra and planetary bulk density / composition. Ephemerides need to be known precise enough to support scheduling of transit spectroscopy.	There are insufficient precision RV resources available to the community to follow up all K2 and TESS candidates that may be relevant to JWST spectroscopic study. Follow up K2 and TESS candidates with quick look low-precision RV screening for false positives (e.g. eclipsing binaries), then high precision (~1-5 m/s) to determined masses of the best candidates. TESS follow-up requires PRV observing time in N and S hemispheres. Overall, TESS will generate ~15k 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, Ap.J.S. 239 2). Modeling of transit timing variations (TTVs) can be used for transiting multi-planet systems; further observations can improve orbits and masses. Transit epochs need to be known to within a few hours.	Keck HIRES limitation for Kepler/K2 exoplanet confirmation is available time, not instrument precision. At 200 new Kepler/K2 validations per year, would need 4 years to achieve 50%. For TESS, initial screening of science team targets is ongoing with LCOGT, Euler, OHP, Magellan/PFS, HARPS and HARPS-N for precise follow-up at ~1 m/s on the best ~100 candidates (expect measured masses for only 50). TTV: e.g. analysis of Kepler multi-planet systems; Spitzer Space Telescope campaign observing transits in 7-planet TRAPPIST-1 system.	The NEID instrument has been delivered to WIYN and is being commissioned at time of writing. Community access is expected to start in 2020A. NASA community access to Keck HIRES and eventually the new Keck KPF instrument. Options for additional southern hemisphere community PRV access are being explored. US community is adding new spectrograph capabilities (e.g. MAROON-X on Gemini-N, etc.).

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)*	Advance screening of targets can determine which stars to prioritize for future exoplanet spectral characterizations. Refine target lists (originally created during concept studies) and improve basic stellar parameters for targets for direct imaging missions taking into account new observations. PRV and/or astrometric observations are desired in order to (1) detect (or constrain presence of) planets for potential spectral characterization, and (2) detect stellar companions which may limit efforts to detect small planets using high contrast imaging. Increasing levels of stellar characterization are needed going from input target star to known exoplanet host star (see SCI-07), in order to prepare for analysis and interpretation of exoplanet spectra.	For the most likely targets of future direct imaging missions, assess the detection limits provided by existing PRV data. Improve these limits through a precision RV observing program in both N and S hemispheres, executed consistently over > 5 years. ESA Gaia mission astrometry (final data release in early 2020s) may reveal evidence of astrometric perturbations by exoplanets which could be targets for direct imaging. Constraints on stellar multiplicity from high resolution imaging needed for assessing whether given star is an adequate target for direct imaging (starlight suppression performance is affected by neighboring stars).	Howard & Fulton (2016, PASP, 128, 4401) completed analysis for 2014 versions of WFIRST, Exo-S, and Exo-C target lists using data from California planet search. Southern target stars are lacking. There are published (and unpublished) RV data for many potential WFIRST 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. Facilities: Keck HIRES, Lick APF, EXPRES, HARPS-N, HARPS, NEID coming online soon. Precursor catalogs: ExoCat-1 represents the most complete publicly available catalog, but is incomplete and becoming out of date. TESS mission has TESS Input Catalog (version 8 is most recent).	EPRV Working Group will recommend precursor observations and datasets which may be added to NExScI Exoplanet Archive. ExEP chief scientists will post new catalog of NASA mission targets (targets identified in studies for direct imaging large and probe mission concepts) to motivate community observations and analysis of these systems. NEID GTO program on WIYN is surveying ~20% of NASA Mission Targets. EXPRES GTO program on DCT is surveying ~10-15% of NASA Mission Targets. Priority of precursor work on WFIRST CGI targets is unclear due to the instrument's current tech demo status.

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 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 the level of exozodiacal dust 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. Mission yield simulations of how the current best estimates of exozodi dust levels affect the integration times and achievable signal-to-noise ratios for 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 images of exozodi disks in the habitable zone would be very valuable, if they were sensitive down to the ~5 zodi level and had the resolution to show substructures and validate theoretical simulations.	Images are available showing the substructure of cold (Kuiper Belt) debris disks as seen by HST, ground adaptive optics, Herschel, and ALMA. 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. subm.), finding a median exozodi level 4× that of the solar system but with a large 1σ uncertainty of 7 zodis. 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 becomes problematic for telescope apertures < 4	The LBTI team is assessing the cost and science value of several upgrades that would increase the sensitivity of their instrument. WFIRST CGI scientists are working to quantify what sensitivity their instrument might be able to achieve to exozodiacal dust in a survey of nearby stars, should NASA decide to re-instate a science program for that instrument. The capabilities of current near-IR interferometers and upcoming ELTs to constrain warm exozodi levels need to be assessed.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
				m if the exozodi level is > +1 σ 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.	
SCI-12	**Measurements of accurate transiting planet radii** *See SPA sections:* *2 (exoplanet populations),* *5 (properties of target stars)*	Measurements of accurate exoplanet radii are important for: classification of planets, estimating their densities, modeling compositions, atmospheres, and spectra, and discovering trends important to understanding planet formation and evolution. The accuracy of measured exoplanet radii is limited by the accuracy of measured stellar radii, which can be dominated by the effects of blending of light by companion stars (some of which may be bound companions). Detailed observations are needed to derive accurate stellar radii. The large number of TESS	High resolution imaging in bulk to validate K2 and TESS candidates. Access to observatories equipped with AO or speckle imaging cameras and turnkey pipelines, is needed in both N and S hemispheres. TESS will discover >15k exoplanet candidates and would need to measure >1k stars/yr to complete the work within a decade. Support work that improves estimation of stellar and exoplanet parameters for discovered exoplanet systems. Supporting photometric and spectroscopic stellar data, along with astrometric, photometric,	NESSI speckle camera at WIYN offers ability to screen a subset of targets to very small separations. SOAR HRCam (speckle), and ground-based AO observations with e.g., Robo-AO, Keck/NIRC2, VLT/NACO, etc. have helped validate KOIs. Gaia DR2 photometry & astrometry resolves bright multiples, and provides parallaxes for improving radii estimates. High resolution spectroscopy can reveal spectroscopic binaries, and injection and recovery tests can place further quantitative	Continued NASA support for community access to speckle cameras on WIYN, Gemini-N and Gemini-S. 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
		exoplanet candidates and high expected contamination rates (20″ pixels) drives requirement for large community effort to measure accurate stellar and exoplanet radii and assess multiplicity. Not accounting for light contamination by neighboring stars, or poor stellar characterization, can lead to exoplanet radii systematically miscalculated at the tens % level. Complete vetting of TESS targets with Kepler approach could take decades. TESS (including FFIs) will generate 10× more candidates than Kepler, and AO and speckle imaging validation of Kepler prime mission candidates took ~3 years. *Improvement in knowledge of other stellar parameters relevant to interpreting exoplanet data is outlined separately in SCI-07.*	and spectroscopic data from latest Gaia data releases, are critical for accurately assessing stellar parameters – and exoplanet radii. For occurrence rate studies, accurate limiting radii for planet detection for transit survey stars for which transiting planets were *not* detected is also important.	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.). SOA reviewed at “Know Thy Star – Know Thy Planet” Conference in 2017.	

APPENDIX A: ACRONYM LIST

ALMA	Atacama Large Millimeter Array
APF	Automated Planet Finder (robotic 2.4-m optical telescope at Lick Observatory)
CGI	Coronagraph Instrument (on WFIRST)
CHARA	Center for High Angular Resolution Astronomy
DR	Data Release
EC	Executive Committee
EEID	Earth Equivalent Insolation Distance (EEID; $a_{EEID} = \sqrt{L}$ au where L is stellar luminosity in solar units)
EPRV	Extreme Precision Radial Velocity
ERS	Early Release Science (JWST program)
ESS	Exoplanet Science Strategy (2018) National Academies Report
ExEP	Exoplanet Exploration Program
Exo-C	Exo-Coronagraph (Probe Study)
Exo-S	Exo-Starshade (Probe Study)
ExoPAG	Exoplanet Program Analysis Group
ExoSIMS	Exoplanet Open-Source Imaging Mission Simulator
ExSDET	Exoplanet Standard Definitions and Evaluation Team
FFI	Full Frame Images
GCM	General Circulation Model
GI	Guest Investigator
GPI	Gemini Planet Imager
GTO	Guaranteed Time Observations
HabEx	Habitable Exoplanet Imaging Mission
HARPS	High Accuracy Radial velocity Planet Searcher
HARPS-N	High Accuracy Radial velocity Planet Searcher-North
HATNet	Hungarian-made Automated Telescope Network
HIRES	High Resolution Echelle Spectrometer
HOSTS	Hunt for Observable Signatures of Terrestrial Planetary Systems
HST	Hubble Space Telescope
HZ	Habitable Zone
IRTF	NASA Infrared Telescope Facility
JWST	James Webb Space Telescope
KELT	Kilodegree Extremely Little Telescope
KPF	Keck Planet Finder
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KOI	Kepler Object of Interest
LBT	Large Binocular Telescope
LBTI	Large Binocular Telescope Interferometer
LCOGT	Las Cumbres Observatory Global Telescope Network
LUVOIR	Large UV/Optical/IR Surveyor

NASA	National Aeronautics and Space Administration
NEID	NN-explore Exoplanet Investigations with Doppler spectroscopy
NESSI	NASA Exoplanet Star (and) Speckle Imager
NExScI	NASA Exoplanet Science Institute
NPOI	Navy Precision Optical Interferometer
PRV	Precision Radial Velocity
PTF	Palomar Transient Factory
RV	Radial Velocity
SAG	Science Analysis Group
SGL	Science Gap List
SMD	Science Mission Directorate
SMP	Single Measurement Precision
SIG	Science Interest Group
SIT	Science Investigation Team
STDT	Science and Technology Definition Team
TBD	To Be Determined
TESS	Transiting Exoplanet Survey Satellite
TPF	Terrestrial Planet Finder
VLTI	Very Large Telescope Interferometer
WASP	Wide Angle Search for Planets
WIYN	Wisconsin, Indiana, Yale, NOAO Observatory
WFIRST	Wide-Field Infrared Survey Telescope