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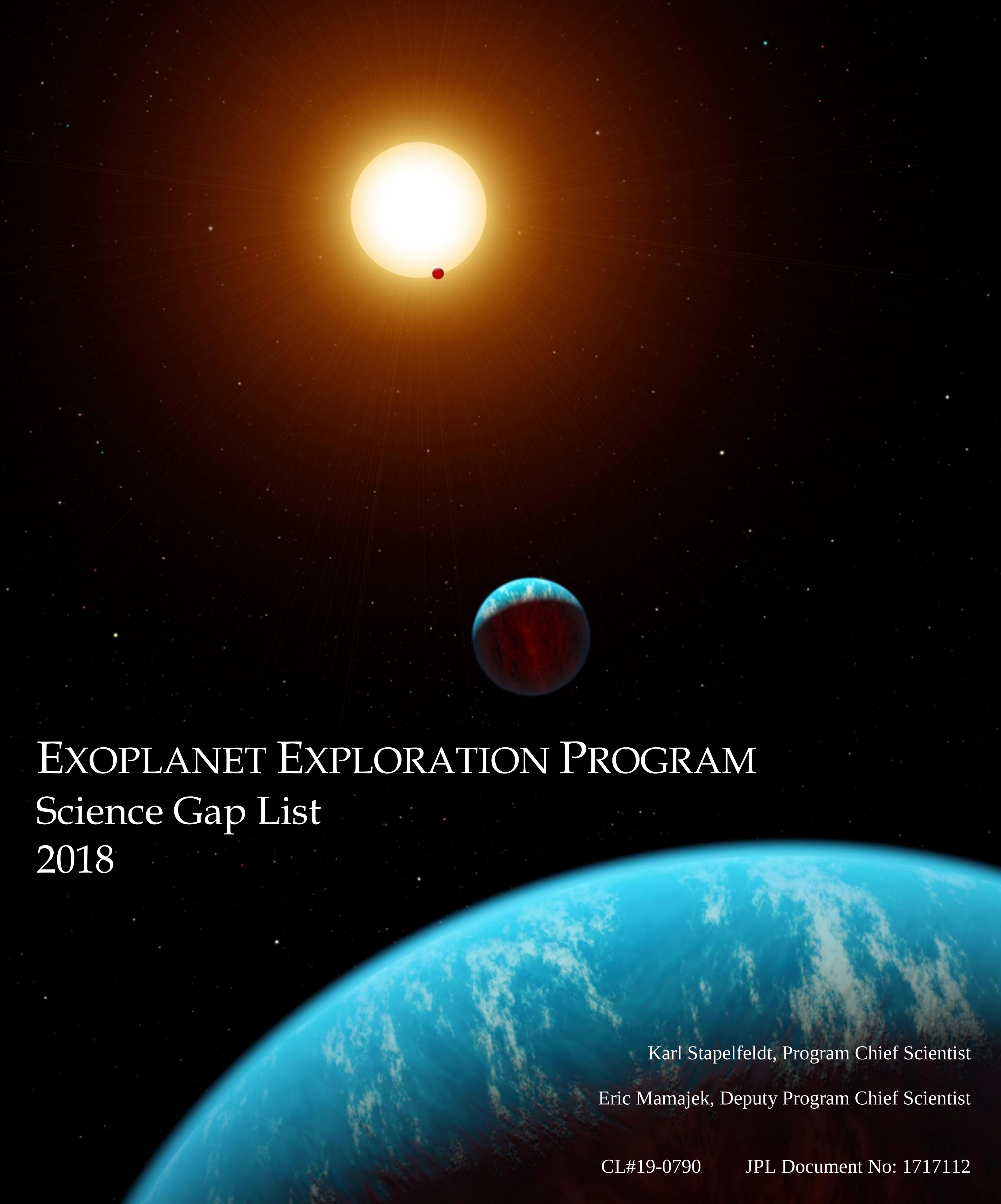

EXOPLANET EXPLORATION PROGRAM

Science Gap List

2018

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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).

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

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The 2018 Exoplanet Exploration Program (ExEP) Science Gap List

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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/.

[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 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's *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 currently considering responses to the *Exoplanet Science Strategy* and *Astrobiology Strategy* reports, but these are not available at the time of writing. 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 overaching 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.

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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)*	There are few extant spectroscopic detections of atmospheres for exoplanets smaller than Neptune, even though they dominate the exoplanet population. The very first constraints are being obtained for the atmospheric composition of terrestrial habitable zone (HZ) planets, but detection of definitive spectral features 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, especially temperate examples, e.g. transit spectroscopy of small planets transiting cool dwarf stars., high-contrast spectroscopy of small, temperate exoplanets orbiting solar-type (FGK-type) stars. Limits to precision on extracting transmission spectra, both instrumental and due to stellar heterogeneities, are described in gap SCI-03. Need target exoplanets that provide the most photons (orbiting nearby, brightest stars for their class). Need accurate ephemerides for scheduling spectroscopic observations and making effective use of large telescopes (e.g. JWST).	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 some super-Earths orbiting very nearest stars. Mission concept studies to define capabilities for next generation of observatory to study atmospheres of small exoplanets via transit spectroscopy (e.g. LUVOIR, HabEx, OST) 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)*	An incomplete understanding of exoplanet spectroscopic signatures impacts ability to interpret observations (e.g. disagreements in interpretations of exoplanet spectra, i.e. clouds vs. metallicity variations vs. extreme C/O ratios vs. non-equilibrium chemistry vs. 3D effects, etc.) and instrumental choices (e.g. resolution, sensitivity, wavelength range, etc.).	Ability to model exoplanet atmospheres and spectra as a function of incident host stellar flux, pressure, composition, clouds, hazes, and illumination phase. How is atmosphere affected externally (by stellar spectrum, winds, etc.) and internally (geology, life)? Challenges include determining composition and properties of aerosols, understanding chemistry (e.g. reaction rates, photochemistry, mixing, etc.), and radiative transfer modeling (including scattering prescriptions) and 3D atmosphere dynamics (e.g. GCM models). Key supporting knowledge provided by the development of molecular and aerosol opacities.	Modeling of individual target systems (e.g. Proxima Cen b). Series of six biosignatures white papers in June 2018 issue of Astrobiology. Modeling of gas giant atmospheres accounting for varying formation mechanisms, disk chemistry, and migration. Extending the latter to 3D circulation models, modeling the impact of nonuniform cloud cover, modeling atmospheric chemistry and escape due to stellar XUV emission and tying models to spectral observations (e.g. HST, JWST, future missions, etc.).	Ongoing research by the community. ExoPAG SAG-10 (Cowan et al. 2015, PASP, 127, 311) quantified the needs and expected results from transit spectroscopy. Support of fundamental research on planetary atmospheres, including origin and evolution of atmospheres, and analysis necessary to characterize exoplanets is under purview of Planetary Science Division (following 2014 NASA Plan). NASA Astrobiology Program and NExSS research coordination network fostering interdisciplinary research on aspects of exoplanet atmospheres and climate relevant to life and biosignatures.

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 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 on contamination of stellar photospheric heterogeneities as limitation to extraction of transiting planet spectra (e.g. Rackham et al. 2018, ApJ, 122, 853).	WFIRST SITs performing retrieval experiments for CGI imaging spectra and community data challenges. 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 uncertain-ties 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.	Community studies are ongoing. Exoplanet Standard Definitions and Evaluation Team (ExSDET) investigating reconciliation of Kepler transit results (e.g. ExoPAG13) with radial velocity survey results.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-05	**Occurrence rates and uncertainties for small planets (eta-Earth)** *See SPA sections: 2 (exoplanet popluations), 5 (properties of target stars)*	Subset of SCI-04 focusing on occurrence rates for Earth-sized planets in HZs, which remains considerably uncertain. Critical to NASA for assessment of next decadal flagship mission for HZ Earth detection.	Analysis of occurrence rates taking into account final Kepler data products (DR25), including effects of stellar multiplicity, Gaia distances, and improved stellar parameters - such that the remaining uncertainties are dominated by intrinsic Kepler systematics.	Published analyses by several authors, including (e.g. Petigura et al. 2013, PNAS, 110, 19273; Burke et al. 2015, ApJ, 809, 8; Traub 2016, arXiv:1605.02255). See ExoPAG SAG 13 final report.	This is an active research area in the community. Kepler mission scientists and community are working on planet occurrence rate studies that incorporate final Kepler DR25 data. Encourage observations which can confirm existence of candidate temperate rocky planets in Kepler data upon which eta-Earth critically relies. Further ahead, a WFIRST microlensing survey may inform this as well.
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. Provide decadal survey with summary comparisons.	Traub (2015) consistent analysis presentation at ExoPAG 12 comparing WFIRST vs. direct imaging probes (Exo-S, Exo-C). Stark (2018) presentation to April NAS Exoplanet Science Strategy committee meeting.	ExSDET is applying the 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	**Improve target lists and compilations of stellar parameters for exoplanet missions in operation or under study** *See SPA section 5 (properties of target stars)*	Improved catalog(s) of stars and relevant properties are important for both ongoing NASA exoplanet missions and concept studies (e.g. for assessing exoplanet yields and sensitivity of proposed mission architectures and instruments). Current catalog for direct imaging mission study yields (ExoCat-1) is incomplete for lower-mass stars and binaries. Flight missions (e.g. Kepler/K2, TESS) have there own input catalogs based mostly on available photometric and astrometric data, however improvement of measurement of exoplanet parameters (e.g. radii, masses, temperatures, etc.) rely directly on improvement of fidelity of stellar parameterization based on photometry, spectroscopy, astrometry, etc., and subsequent analysis.	For exoplanet imaging mission concepts, a complete census of nearby stars that may be potential targets for imaging exoplanets (with architecture-dependent parameter limits), especially those in HZs, is needed. Basic stellar data is required, including distance, luminosity, temperature, multiplicity, known planets or detection limits. Knowledge of XUV emission and age can improve modeling of exoplanet atmospheres and evolution and interpretation of planet spectra. Binary information (brightness, separation, etc.) is important as many targets are binaries. For potential transit or transit spectroscopy/photometry missions, more general catalogs of stellar targets and/or exoplanet host stars over wider range of distances may be needed. Catalogs should account for most recent Gaia data.	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. SOA for complete volume-limited samples is 8 pc sample from Kirkpatrick et al. (2012, ApJ, 753, 156), but lacks important stellar parameters. ExoCat-1 hosted at NExScI Exoplanet Archive represents the most complete publicly available catalog, but is missing information and is becoming out of date.	ExEP science office assisting ExSDET on updating/checking multiplicity data for nearby star catalog. NExScI Exoplanet Archive is actively compiling data on exoplanets and their host stars, and will include parameters taking into account new Gaia distances and other measurements. Note: SCI-07 focusses on target lists for studies & supporting improvement of input catalogs for mission surveys, whereas SCI-12 is for detailed (resource/time-intensive) characterization of host stars of exoplanet candidates.

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. Stellar jitter (spots, plage, granulation, non-radial oscillations, etc.) is an ever-present source of noise over a variety of timescales for both PRV and astrometric methods. PRV is currently the predominant means of dynamically measuring masses of exoplanets, and stellar jitter is currently the tallest tentpole in the PRV uncertainty budget. 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 sub-μas-level, then astrometry could provide an	**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. Likely requires large (>4m-class) telescopes and heavy commitment of observing time. Need new analysis methods to correct for stellar RV jitter using high spectral resolution and broad spectral coverage. PRV datasets for the Sun may enable testing and improvement of mitigation strategies. **Astrometry:** Exo-Earth orbiting 1 M_{Sun} star at 10 pc induces amplitude of ~0.3 μas. For Sun-like activity levels, astrometric jitter would be ~0.05 μas – small, but not negligible (but higher for more active	**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 (Aug 2017). **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 for WIYN (northern hemisphere 4-m class). SAG-8 (Plavchan, Latham et al. 2015; arXiv:1503.01770) discussed effective use of the resources needed for confirming exoplanets. Detection of Earth-like exoplanets in HZs may require major new instrument with TBD spectral resolution and wavelength coverage.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-08 (cont.)		alternative method which could yield orbits and masses for rocky planets around nearby stars.	stars). Develop capability to perform precision astrometry on nearby bright stars as precursor or followup for flagships and possibly WFIRST-CGI, 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 popluations), 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.	There are insufficient precision RV resources available to the community to follow up all K2 and TESS exoplanet 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 will require PRV observing time in N and S hemispheres. Overall, TESS will generate ~15,000 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, arxiv/1804.05050). Modeling of transit timing variations (TTVs) can be used for transiting multi-planet systems; further observations can improve orbits and masses.	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 already planned for LCOGT, Euler, OHP. HARPS and HARPS-N planned 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.	NASA community access to Keck HIRES and eventually the new Keck KPF instrument. The NEID instrument for WIYN is in development, with commissioning in 2019A and community access in 2019B. Options for additional southern hemisphere community PRV access are being explored. US community 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 surveys of direct imaging targets** *See SPA sections: 3 (exoplanet dynamics), 5 (properties of target stars), 6 (atmospheres & biosignatures)*	Advance screening of targets (especially via PRV) can determine which stars to prioritize for future exoplanet spectral characterizations. Insufficient community work to inform future missions.	For the most likely targets of future direct imaging missions, assess the detection limits provided by existing RV 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, ~2022) may reveal evidence of astrometric perturbations by exoplanets among some nearby stars which could be targets for direct imaging.	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. Keck HIRES, Lick APF, HARPS-N and HARPS.	Community contributions of precision RV datasets into NExScI Exoplanet Archive? NEID GTO program may cover a subset of these targets. Does WFIRST CGI's new tech demo status undermine the rationale for this effort – should this be a priority?

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)*	Exozodi dust is a noise source affecting the ability to image HZ rocky planets around nearby stars (spectroscopy integration times, science yields). Substructure in the exozodi may mimic exoplanets in low angular resolution images and thus confuse searches for HZ planets with smaller apertures. Images of habitable zone dust structures do not yet exist.	Simulations are needed of how the LBTI HOSTS exozodi survey results affect integration time for large mission concept studies and WFIRST, as a function of instrument parameters. Simulations of scenes as viewed by a future flagship missions, quantifying the effectiveness of multi-epoch observations to discriminate exozodi clumps from planets. Direct images of exozodi disks in the HZ ~5 zodi level and with sufficient resolution and sensitivity to image substructure and validate the simulations?	See Ertel et al. (2018, AJ, 155, 194) interim results on LBTI HOSTS survey of exozodi dust, and simulations by Stark et al. (2015, ApJ, 808, 149; 2016, SPIE, 99041U) of effects of exozodi on mission exoplanet yields. Theoretical models of planet-induced structure. Imaging of structure in outer debris disks with HST, ground AO, ALMA, comparisons with dynamical simulations.	LBTI HOSTS survey was completed mid-2018 and will be followed by analysis of full survey data. Mission yields will need to be recalculated incorporating constraints from final HOSTS results. Roberge et al. (2012, PASP, 124, 799) and ExoPAG SAG-1 report. Potential option for WFIRST CGI imaging of exozodi clouds in mid-2020s.

ID	Title	Summary	Capability Needed	Capability Today	Mitigation in Progress
SCI-12	**Measurements of accurate transiting planet radii** *See SPA sections: 2 (exoplanet popluations), 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. Contamination to light curves by neighboring stars and poor stellar characterization can preclude accurate radii measurement. TESS (including FFIs) will generate 10x more candidates than Kepler, and with acute confusion problem (20” pixels). AO and speckle imaging validation of Kepler prime mission candidates took 3 years. Complete vetting of TESS targets with Kepler approach could take decades. Besides imaging, there is also the challenge of assessing accurate stellar radius via observations (photometry, spectroscopy) and subsequent analysis.	High resolution imaging in bulk to validate 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/year required to complete the work within a decade. Support work that improves estimation of stellar and exoplanet parameters for discovered exoplanet systems. Including 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 ultimately exoplanet radii.	NESSI speckle camera at WIYN offers ability to screen a subset of targets to very small separations. Robo AO operated at Kitt Peak to validate KOIs, now offline (revival at IRTF?). Gaia DR2 photometry & astrometry resolves bright multiples, and provides parallaxes for improving radii estimates. For improving knowledge of host star T_{eff}, metallicity, gravity: high-res. spectroscopic surveys (e.g. California-Kepler survey), low-res. spec. surveys (e.g., APOGEE & LAMOST), community access to spectrographs for extracting stellar spectra (e.g. Keck HIRES, NEID, etc.). SOA reviewed at “Know Thy Star – Know Thy Planet” Conference in 2017.	Continued NASA support for community access to speckle camera on WIYN (NN-Explore program) in NEID era. Note: SCI-12 is for detailed (resource/time-intensive) characterization of host stars of exoplanet candidates, whereas SCI-07 focusses on target lists for studies & supporting improvement of input catalogs for mission surveys.

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
ERS	Early Release Science (JWST program)
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