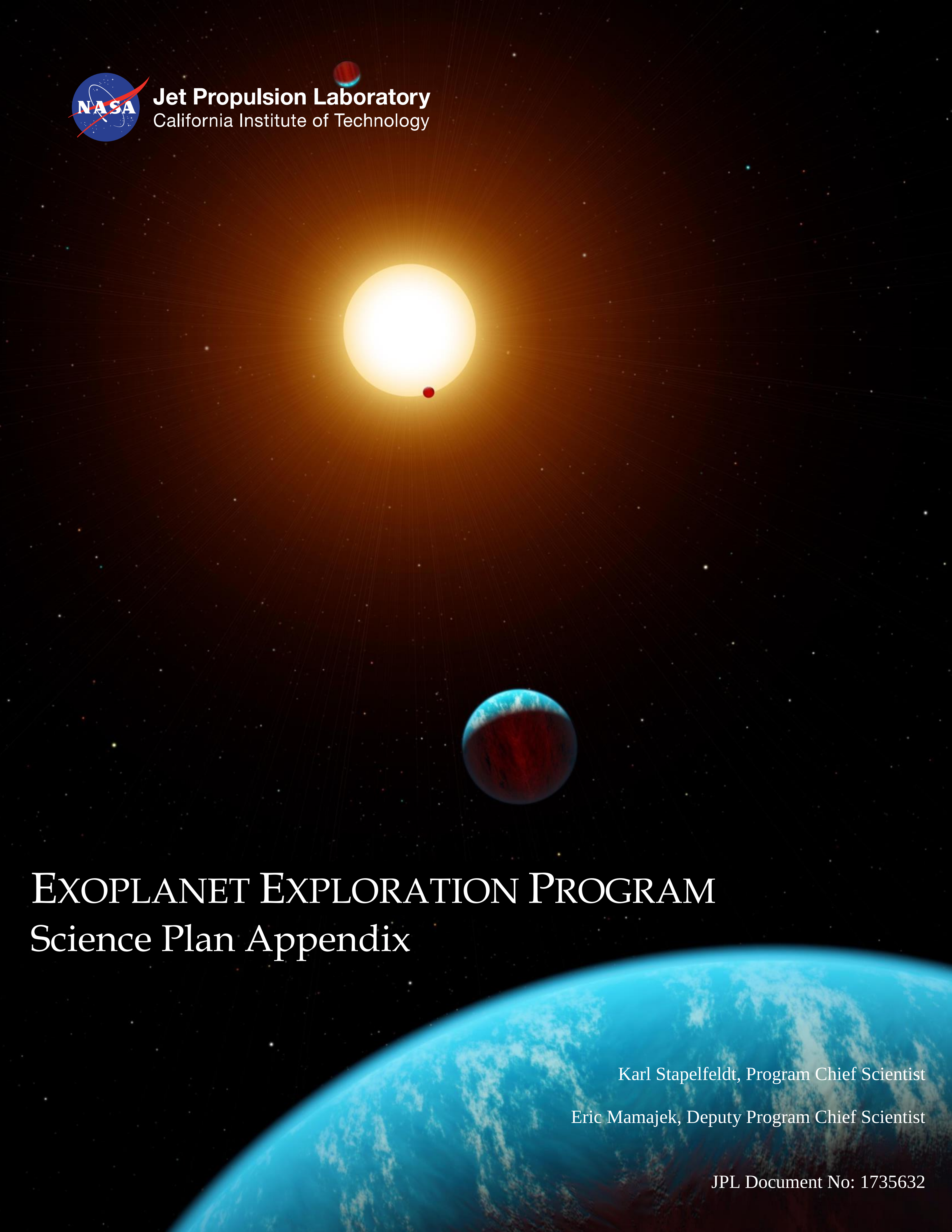

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EXOPLANET EXPLORATION PROGRAM
Science Plan Appendix

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1. Introduction

1.1. The NASA Exoplanet Exploration Program (ExEP)

The NASA Exoplanet Exploration Program (ExEP) is a focused program within the Astrophysics Division (APD) of the NASA Science Mission Directorate (SMD), and defined within the NASA Science Plan [1]. The NASA Exoplanet Exploration Program (ExEP) is managed as a NPR 7120.8 NASA Research and Technology Program. The Exoplanet Exploration Program advances science and strategic planning relate to the broad scientific question "*Are we alone?*" [1]. ExEP's three aims are:

- *discovering planets around other stars,*
- *characterizing their properties, and*
- *identifying candidates that could harbor life*

Exoplanet exploration is integral to the objectives of the the 2018 NASA Strategic Plan. The 2018 NASA Strategic Plan defines *Strategic Objective 1.1: Understand the Sun, Earth, Solar System and Universe*. Efforts under Stategic Objective 1.1 are "*guided by National priorities and recommendations form the National Academies's decadal surveys and implemented through a balanced portfolio of programs*", with Science Mission Directorate (SMD) being the lead office. "*The success criteria for SMD are progress in answering fundamental science questions, implementing the decadal survey priorities, and responding to direction from the Executive Branch and Congress*." As of 2018, the most recent version of the decadal survey setting priorities for Astronomy & Astrophysics is the 2010 report *New Worlds, New Horizons in Astronomy and Astrophysics* [2]. Exoplanet science falls under two of the three core contexts of NASA's first strategic objective: "*Discovering the Secrets of the Universe"* (where understanding exoplanets is part of understanding "*the universe beyond*") and "*Searching for Life Elsewhere?*". The 2018 NASA Strategic Plan states:

"Observations from SMD's astrophysics missions have made it clear that habitable planets exist around stars other than the Sun and that such planets are plentiful. Improving techniques and ideas for discovering and characterizing habitable and/or inhabited environments on these planets, coupled with an understanding of the potential false positives for habitability of life, will enable prioritization of exoplanets for targeted follow-up observations. This will help push frontiers in the coming decades of discovery and enable the search for signs of life on worlds that may be capable of harboring life, both within our own solar system and within the galaxy."

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 this document.

The goal of the ExEP Science Plan is to show how the Agency can focus its science efforts on the work most needed to realize the goal of finding and characterizing habitable exoplanets, within the context of community priorities. The ExEP *Science Plan* consists of three documents, which will be updated periodically, which respond directly to the ExEP Program Plan [4]:

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

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

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

The 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.

This document, 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 every two years.

1.2. Science Investigation Areas Relevant to ExEP Objectives

The ExEP science objectives can be subdivided into several investigation areas, which are discussed in the following subsections: 2 exoplanet populations, 3 exoplanet dynamics, 4 exozodiacal dust, 5 properties of target stars, and 6 exoplanet atmospheres and biosignatures. For each of these areas, this chapter reviews the current state, upcoming progress, and investigations still needed to address ExEP's near-term and long-term objectives. The discussion provided herein provides the context for the ExEP Science Gap List, against which new proposed work is measured.

While there are important science questions of general interest for understanding exoplanets, there are two science questions that are important for practical reasons. These questions are: *What are the levels of exozodiacal dust orbiting nearby stars? What is the occurrence rate of Earth-sized planets orbiting within the habitable zones of nearby stars?* The answers to these important questions feed into important strategic decisions on the mission architectures needed to tackle NASA's long-term goals of imaging and spectrally characterizing potentially habitable exo-Earths around nearby stars.

2. Exoplanet Populations

The exoplanet field is less than a generation old, and astronomers have gone from being able to study only a single planetary system as of the late 1980s to a few thousand systems as of the late 2010s[1]. Averaged out over the past three decades, the number of exoplanets is doubling approximately every 27 months, with on-going and proposed surveys likely to continue this trend discovering tens of thousands of exoplanets during the 2020s. A recent review of exoplanet demographics, presented by discovery technique, appears in the 2018 National Academies report *Exoplanet Science Strategy*, pages 2-6 to 2-14 [3]. Exoplanet discoveries in recent years have provided a bewildering array of different planet properties and new categories of planets that do not exist in our solar system (e.g. hot Jupiters, eccentric Jupiters, super-Earths, sub-Neptunes, etc.). *What are the various types of exoplanets and how do they form? What are the distributions of exoplanet masses, radii, and composition, as functions of stellar mass, spectral type, stellar chemical composition, and stellar multiplicity*? Specifically, determining the statistical frequencies of "Earth-size" rocky exoplanets as functions of these stellar parameters are critical for planning future flagship missions proposed for imaging exo-Earths orbiting nearby stars.

Most exoplanet detection methods are dynamical in nature, and will be discussed at length in Sec. 3. In this section, we'll focus on the statistical properties of the exoplanet populations, i.e. their frequency and demographics as informed by the various detection methods.

> *"Is the typical outcome of planet formation gas-giant worlds with panoplies of satellites, like Jupiter and Saturn, or rocky worlds like Earth with atmospheres and surface liquids stabilized by being suitably near to stable parent stars like the Sun, or some completely different kind of object that is not represented in our solar system? The answer to this question will require a complete census of planetary systems in the nearby portion of our galaxy. By compiling the statistics of planetary sizes, masses, and orbits for a range of planetary systems around stars of different masses, compositions, and ages, it will be possible to gain deep insight into the processes by which worlds such as our own come into being."*
>
> *New Worlds, New Horizons in Astronomy & Astrophysics (2010)*

> *"Profound questions that can be addressed include the following: What physical processes primarily determine the diverse outcomes of planet formation and how common are systems like the Solar System? What interior, surface, and atmospheric compositions typically result from these processes? In other words, what are the properties of planets orbiting stars in the solar neighborhood?What planetary, stellar, and planetary system properties determine habitability, and how do planet formation processes shape the distribution of habitable environments in the galaxy? How common are potential biosignature gases and signatures of disequilibrium chemistry in the atmospheres of extrasolar planets? Are theoretical suggestions that these signatures will be signposts of life consistent with the observed behavior of planetary atmospheres?"*
>
> *NAS Exoplanet Science Strategy (2018)*

[1] Data and plots that are updated daily on the demographics of exoplanets that have been discovered, broken down by planet parameters, star parameters, discovery and characterization data, are compiled at the NASA Exoplanet Archive at https://exoplanetarchive.ipac.caltech.edu/.

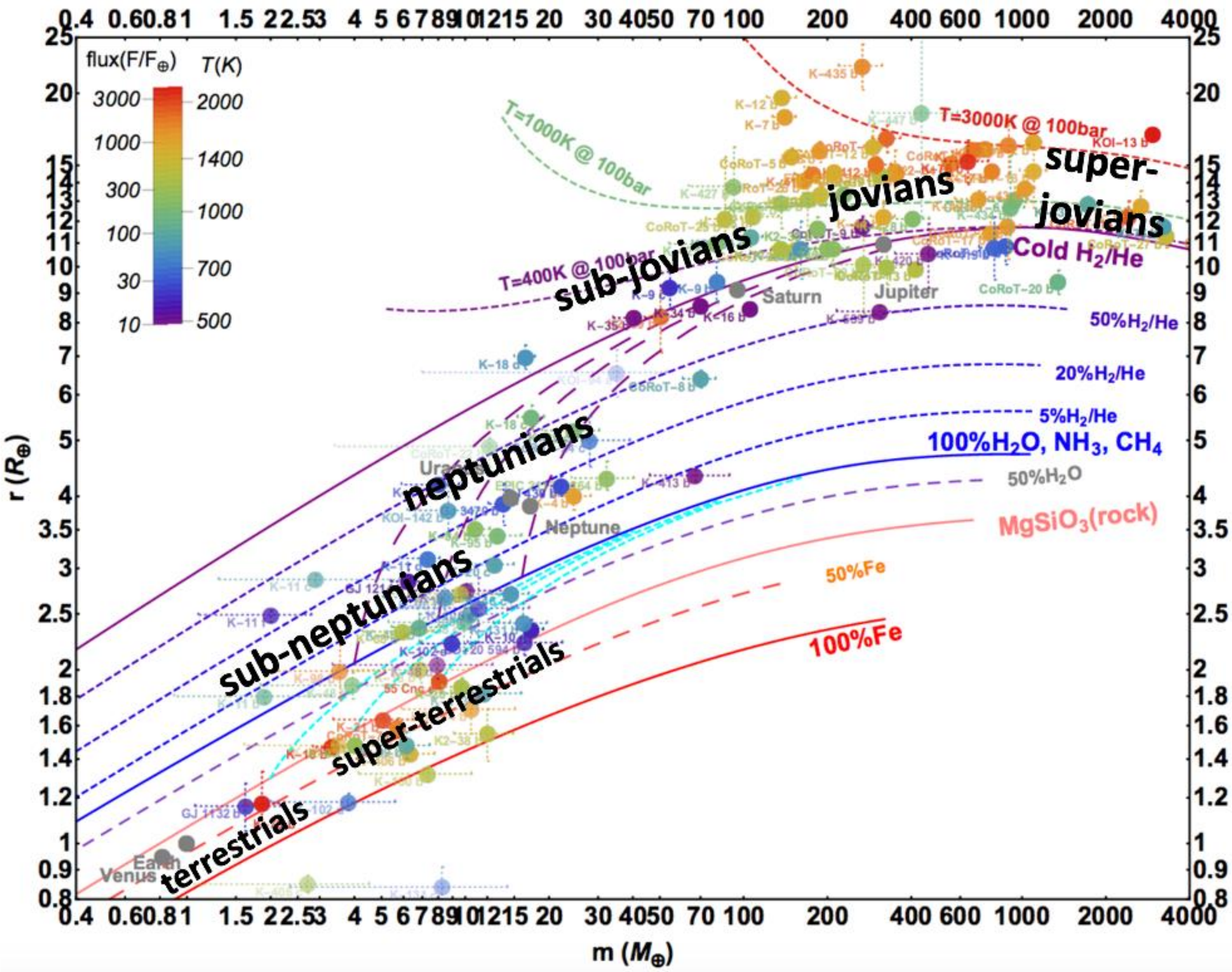

Figure 1: Exoplanet mass versus radius, from Li Zeng (2017; https://www.cfa.harvard.edu/~lzeng/planetmodels.html; see also** [5]**). Descriptive types that sometimes appear in the literature are overlain in black.

2.1. Populations: State of the field

Different observational techniques are sensitive to different exoplanet populations, and so the results from surveys using these different techniques have been needed to identify exoplanets of different types[2]. Surveys from various techniques need to be combined to synthesize statistical distributions describing exoplanet frequency. Besides mere statistical distributions of exoplanetary

[2] The NASA Exoplanet Archive maintains a compilation of planet occurrence rate papers at: https://exoplanetarchive.ipac.caltech.edu/docs/occurrence_rate_papers.html.

parameters, there are degeneracies in their properties which can preclude proper characterization of a planet if only one parameter is measured (e.g. mass or radius; see Figure 1). Exoplanets in the mass range ~2-20 M_{Earth} could either be rock-dominated super-terrestrial planets ranging to sub-neptunian planets with thick H/He-dominated envelopes, with radii differing by tens of percent [6]. Likewise, a ~10 R_{Earth} exoplanet could correspond to a gas giant planet anywhere in mass between ~0.1 M_{Jup} all the way well into the brown dwarf regime (tens of M_{Jup}) [7]. Statistical distributions of mass or radius of exoplanets *alone* are not sufficient to reliably categorize planets by "type".

The distribution of estimated orbital semi-major axes versus planet radii are plotted for confirmed exoplanets in the NASA Exoplanet Archive in Figure 2. Many more planets are known than plotted, where one or both parameters has not been estimated or quoted in the literature. Figure 2 illustrates the sensitivity of the different techniques to detecting planets of various sizes and orbital periods (or separations). Transit surveys like Kepler/K2 are sensitive mostly to close-in, highly irradiated exoplanets, biased towards larger radii objects. Precision radial velocity surveys are sensitive mostly to close-in massive exoplanets, however long-term monitoring has been able to discover massive exoplanets on orbital periods of decades. Direct imaging has, thus far, been mostly been sensitive to large, young giant exoplanets on wide orbits (tens to hundreds of astronomical units). Microlensing is sensitive to exoplanets with a wide range of masses down to those of small rocky planets at intermediate orbital separations (few AU), and promises to help astronomers statistically bridge the gap in our knowledge of exoplanet frequencies between the close-in transit and radial velocity-discovered exoplanet populations and the distant, direct-imaging-discovered exoplanets. No single exoplanet discovery technique is capable of fully

"…exoplanet astronomy is one of the most rapidly developing and unpredictable fields in modern astronomy. Both the statistical investigations of Kepler and WFIRST, and the location of specific, nearby, potentially habitable Earth-like planets under a strong yet flexible program of ground-based research, are recommended. This combined approach will allow new techniques to be devised and surprising discoveries to be made during the coming decade."

New Worlds, New Horizons in Astronomy & Astrophysics (2010)

"One of the fastest growing and most exciting fields in astrophysics is the study of planets beyond our solar system. The ultimate goal is to image rocky planets that lie in the habitable zone of nearby stars—at a distance from their star where water can exist in liquid form—and to characterize their atmospheres. Detecting signatures of biotic activity is within reach in the next 20 years if we lay the foundations this decade for a dedicated space mission in the next. Achieving this ultimate goal requires two main necessary precursor activities. The first is to understand the demographics of other planetary systems, in particular to determine over a wide range of orbital distances what fraction of systems contain Earth-like planets. To this end, the committee recommends, as discussed earlier in this chapter, combined exploitation of the current Kepler mission, development and flight of the first-priority large mission WFIRST, and a vigorous ground-based research program."

New Worlds, New Horizons in Astronomy & Astrophysics (2010)

characterizing the exoplanet population across the full range of masses and orbital separations of planets seen in our solar system (~0.05-318 M_{Earth}; ~0.4-30 au).

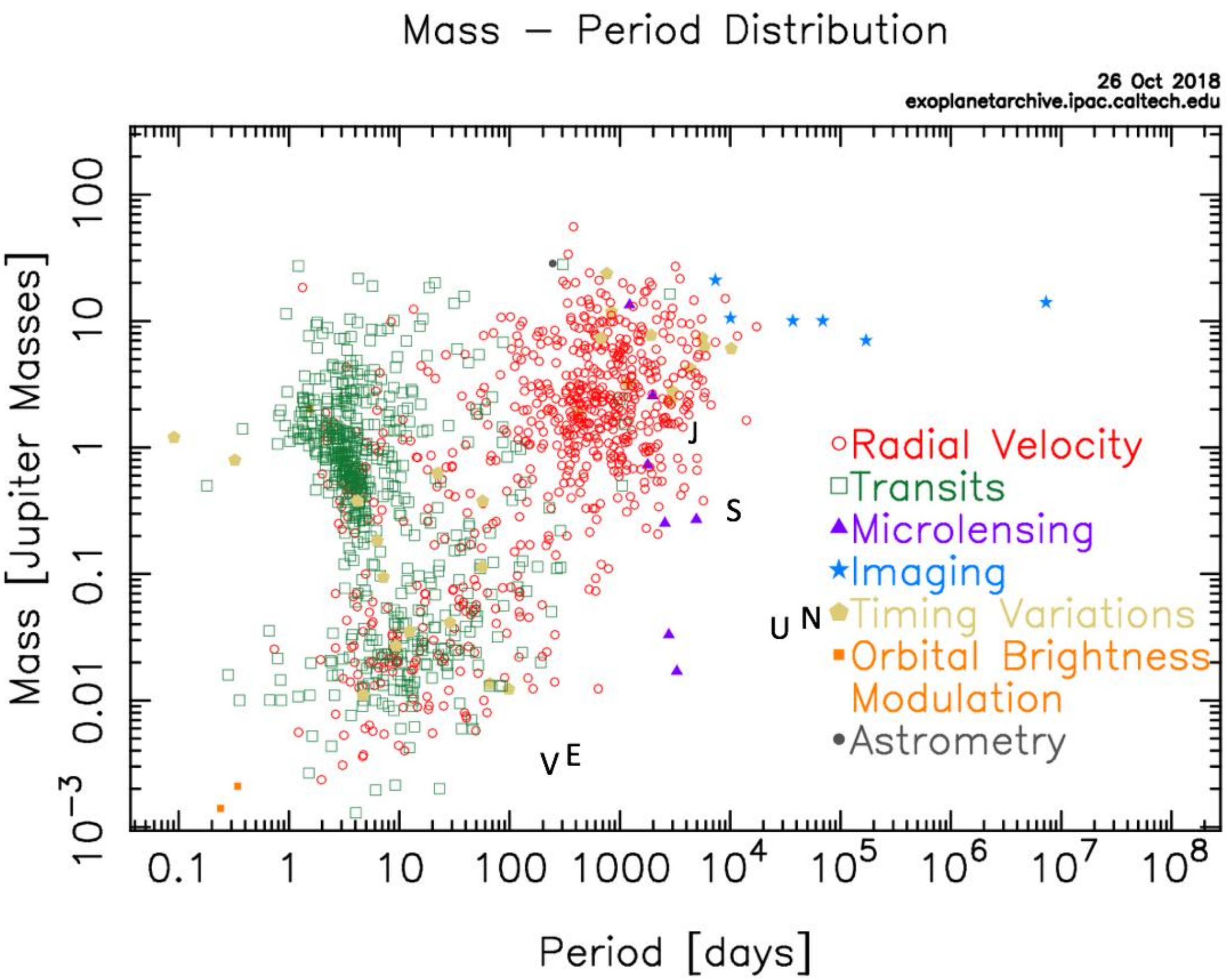

Figure 2: Orbital period vs. mass for subsample of confirmed planets in the NASA Exoplanet Archive which have published periods and masses. Many more planets are not plotted which are missing published estimates of one or both parameters (e.g. many of the Kepler and K2 transiting planets do not yet have measured radii, most papers on microlensing planets do not quote orbital periods in favor of semi-major axis, etc. Solar system planets Venus (V), Earth (E), Jupiter (J), Saturn (S), Uranus (U), and Neptune (N) are plotted for comparison.

Interesting trends have emerged from surveys of exoplanets over the past two decades that have spurred new theoretical interpretation and modeling. Gas giant exoplanets with periods shorter than a few years can be found around ~10% of stars similar to the Sun [8]. Exoplanets smaller than Neptune (~4 R_{Earth}) can be found around ~50% of Sun-like stars, and closely packed systems with multiple planets are common [8]. The frequency of gas giant ("jovian") exoplanets orbiting Sun-like stars is proportional to the metal content of the host star [9], which has been interpreted as evidence for the core accretion scenario for giant planet formation being the dominant mechanism [10]. The frequency of "hot Jupiters" and "hot rocky planets" with periods of <10 days appears to increase with correspondingly increased stellar metallicity [11]. The frequency of gas giant exoplanets larger than 4 $M_{Jupiter}$ appears to be independent of stellar metal composition, and may constitute a separate population of "super-jovian" exoplanets which forms via a different mechanism [12], possibly related to gravitational instability [13]. Two of the most remarkable findings of the Kepler mission (among many others) are that exoplanets intermediate in size between the Earth and Neptune are the common, dominant population found close-in to Sun-like stars [14], and that upon refinement of the stellar parameters and exoplanet radii, two peaks emerge – consistent with rock-dominated "super-Earths" (~1.25-1.7 R_{Earth}) and H/He-enveloped "sub-Neptunes" (~2-3 R_{Earth}) [15]. The so-called "Fulton gap" in the distribution of exoplanet radii near ~1.7 R_{Earth} [15] has been interpreted as marking the empirical division between rock-dominated exoplanets and those that have H/He envelopes – where even modest H/He mass fractions (~1-2%) can increase planetary radii by tens of percent [16]. As Figure 1 illustrates, there is likely to be a bewildering range of planet types between approximately ~2 and ~20 M_{Earth}, and the extrema are remarkable compared to solar system planets. There appear to be close-in sub-neptunian exoplanets with tens of percent H/He by mass, with masses as low as ~2 M_{Earth} and radii of ~2-3 R_{Earth}, while at the same time rock-dominated super-terrestrial exoplanets exist with masses of up to ~20 M_{Earth} and radii of ~2 R_{Earth}. The "periodic table" of exoplanet types in the Galaxy may have its most complex region of physical characteristics in the range of masses and radii between that of Earth and Neptune (~4 R_{Earth}, ~17 M_{Earth}) and yet these populations of super-terrestrial and sub-neptunian exoplanets have no counterpart in our solar system that we can study up close. The early evolution and prospects for habitability of rocky planets that have thin H/He envelopes is still an active field of research [17]. Further measurements of stellar properties from ground-based spectroscopy, improvements in spectral classification and distances from Gaia, surveying for stellar companions which may contaminate light curves and exoplanet radii estimates, improving dynamical estimates of exoplanet masses, etc. will all help probe this interesting region of exoplanet parameter space much more accurately, and enable testing of interiors models of varying compositions.

Of particular interest in the field of exoplanet populations are the small, potentially habitable rocky worlds which may be able to retain surface liquid water. Astronomers have been using results from the Kepler mission to infer the frequency of Earth-sized planets in the habitable zone of Sun-like stars ($\eta_\oplus$) [18]. In order to help inform exoplanet yield estimates for mission concept studies in a consistent manner, the ExoPAG SAG13 group has defined $\eta_{habSol,SAG13}$ as the frequency of exoplanets orbiting Sun-like stars with radii in the range 0.5-1.5 R_{Earth} and orbital periods of 237 to 860 days. This range of periods corresponds to the range of an optimistic empirical habitable zone (bracketing the cases of "recent Venus" and "early Mars") [19]. As of June 2017 ExoPAG meeting, the SAG13 group has quoted an average occurrence rate of $\eta_{habSol,SAG13} = 0.58^{+0.7}_{-0.2}$, based on a meta-analysis of planet frequency distributions estimated by a dozen studies of the Kepler data[3]. The value is very sensitive to the power-law size distribution of exoplanets between Earth- and Mars-sized, which is not well-constrained by the Kepler data in the relevant period

[3] This value reflects the SAG13 results as of the ExoPAG16 meeting in June 2017. All of the studies in the SAG13 analysis as of mid-2017 had included earlier Kepler exoplanet candidate catalogs, and none had yet included the final Kepler DR25 data products. The SAG13 online tool for estimating planet frequency as a function of planet radius and orbital period is currently posted at: http://www.princeton.edu/~rvdb/SAG13/SAG13.html.

range. At the time of writing, the Exoplanet Standard Definitions and Evalulation Team (ExSDET), chartered to provide consistent science yield analyses for the large mission concept studies in preparation for the 2020 Astrophysics Decadal Survey, is using a somewhat more conservative estimate of the frequency of exo-Earths. At the time of writing, the ExSDET has adopted an "exoEarth candidate" planet radius range with maximum radius 1.4 R_E (recognizing that R > 1.5 R_E planets are unlikely to be rocky [20, 15]) and a minimum radius varying from ~0.6 to 0.8 R_E, corresponding to the empirical "Cosmic Shoreline" dividing planetary bodies with and without atmospheres [21]. The inner and outer habitable zone boundaries correspond to the revised conservative boundaries from [19] for the "moist greenhouse" and "maximum greenhouse" cases, respectively, with inner and outer orbital radii of 0.99 and 1.67 au, respectively, for the current solar luminosity (and orbital periods of 360 days to 788 days, respectively). For this more conservative "box" of planetary radius and orbital radius (for a nominal star with solar properties) drawn from the SAG13 planet frequency distribution, the planet frequency of "candidate exo-Earths" corresponds to $\eta_\oplus = 0.25^{+0.25}_{-0.08}$. This value is notably higher than that used in studies from a couple years ago, e.g. that adopted for the 2015 Exo-C and Exo-S probe studies, of $\eta_\oplus$ = 0.1.

2.2. Populations: Current and upcoming activities

Different missions and surveys are providing different pieces of the exoplanet populations puzzle. Kepler and K2 has been informing astronomers about the distribution of sizes and orbital periods for close-in planets (periods < year). TESS will discover thousands of very close-in exoplanets (periods < months) which will be amenable to radial velocity follow-up to enable mass determinations [22]. Ongoing radial velocity programs have been surveying many of the nearby Sun-like stars for upwards of two decades [23], and are now capable of identifying giant planets with Jupiter-like masses and orbital separations (~5 AU) [24], and are now capable of detecting Earth-mass exoplanets in the habitable zones of some nearby M dwarfs [25]. Results of radial velocity surveys taking into account long-term velocity trends suggest half of systems known to have a Doppler-detected within 5 AU of Sun-like stars are likely to have 1-20 $M_{Jupiter}$ companions further out (5-20 AU) [26]. The NEID spectrograph, as part of the NN-EXPLORE program on the WIYN observatory, will soon enable the community to investigate the exoplanet populations with Doppler spectroscopy to unprecedented radial velocity precision. Radial velocity follow-up and transit timing variations (in transiting multi-planet systems) are yielding dynamical mass estimates for exoplanets, and hence their bulk densities, which can constrain planet composition models and statistically constrain mass-radius relations in some parts of planet parameter space [5].

"First, the frequency with which Earth-size planets occur in zones around stars where liquids such as water are stable on planetary surfaces must be measured…"

"How diverse are planetary systems?"

New Worlds, New Horizons in Astronomy & Astrophysics (2010)

"However, in addition to determining just the planetary statistics, a critical element of the committee's exoplanet strategy is to continue to build the inventory of planetary systems around specific nearby stars. Therefore, this survey strongly supports a vigorous program of exoplanet science that takes advantage of the observational capabilities that can be achieved from the ground and in space."

New Worlds, New Horizons in Astronomy & Astrophysics (2010)

Microlensing is a critical method for characterizing exoplanet populations at orbital separations larger than those probed by the transit and radial velocity methods, and closer in and to lower masses than direct imaging can probe [27, 28]. A few dozen exoplanet candidates have been discovered via ground-based microlensing surveys thus far, however surveys of Galactic star fields by the Euclid and WFIRST missions in the 2020s should uncover hundred to thousands of exoplanets via microlensing, and draw statistical conclusions about the distribution of exoplanet masses as a function of orbital separation at those intermediate orbital separations for stars in the Milky Way's disk and bulge [29]. Microlensing can also constrain the population of "rogue planets" or "nomads" drifting through the Milky Way [30], which can help constrain models of the formation of exoplanetary systems and their early dynamical evolution [31].

ESA's Gaia astrometric mission is projected to yield of order ~10^4 exoplanets of ~1-15 $M_{Jupiter}$ at orbital separations of ~1-5 AU around stars typically tens to hundreds of parsecs away [32]. Gaia is also sensitive to giant planets orbiting higher mass stars than traditionally surveyed by Doppler spectroscopy programs. Given the relative rarity of gas giant planets, combining the Gaia exoplanet yields with ground-based Doppler spectroscopy program results should further test whether multiple formation mechanisms are at work forming giant planets [12]. Ground-based direct imaging surveys have mostly yield young giant planets at wide separations (~10-100s AU) [33], however JWST may be able to observe thermal emission from young Saturn-mass exoplanets on wide orbits of nearby stars [34]. WFIRST will likely discover a small number (~3-12) of new exoplanets missed by Doppler surveys [29].

The TESS full-frame images (FFIs) will provide light curves for ~10^7 stars, two orders of magnitude more stars than the Kepler prime mission, and should enable the discovery of more than ~10,000 exoplanets with radii >2 R_{Earth} in close-in orbits [35]. This will enable more statistical analysis of trends for close-in planet populations as functions of stellar mass, age, and chemical composition which should further inform planet formation and evolution models [36].

"An equally important outcome [of WFIRST] will be to open up a new frontier of exoplanet studies by monitoring a large sample of stars in the central bulge of the Milky Way for changes in brightness due to microlensing by intervening solar systems. This census, combined with that made by the Kepler mission, will determine how common Earth-like planets are over a wide range of orbital parameters."

New Worlds, New Horizons in Astronomy & Astrophysics (2010)

2.3. Populations: Knowledge needed to inform ExEP Objectives

There is broad scientific interest in observing the diversity of exoplanets and exoplanetary system architectures as a function of stellar type and stellar age, to reveal the full range of outcomes of the planet formation process. Because each exoplanet detection technique has its own sensitivity biases, progress in population studies will broadly require improvements in all exoplanet detection methods and facilities. The Exoplanet Exploration Program seeks the development and full exploitation of exoplanet discovery surveys using all methods (transit, radial velocity, microlensing, imaging, astrometry), particularly targeting regions of parameter space that are inadequately probed to date: rocky planets in habitable zones, planets beyond the snow line, planets around young stars, and the detection of solar system analogs.

It is especially important to extend population surveys down to planet sizes and masses comparable to that of the Earth. The Kepler mission showed that 2-3 R_E planets are common interior to the HZ, but detected relatively few Earth-sized planets within habitable zones themselves. The Exoplanet Exploration Program seeks a robust statistical understanding of exoplanet occurrence rates and their uncertainties, particularly for HZ rocky planets, as applicable to the host star population within 30 pc of the Sun. Studies combining population results from multiple exoplanet detection methods will be especially useful toward this goal. These occurrence rates are of fundamental importance to selecting the architectures, estimating the required observing times, and predicting the exoplanet yields that can be achieved by future large telescopes designed to pursue exoplanet spectral characterizations.

Transiting exoplanets form the bulk of the currently known exoplanets. With the launch of TESS and the upcoming PLATO mission, this is likely to be true for decades to come. To overcome low transit probabilities, these survey missions maximize their fields of view to observe large numbers of stars, at the price of significant confusion from multiple background objects blended together in the target star measurements. The Exoplanet Exploration Program seeks an active program of groundbased follow-up observations to validate transit survey detections and measure the host star properties so that the masses and radii of transiting exoplanets are well-measured.

SCI-04 Planetary system architectures: occurrence rates for exoplanets of all sizes
SCI-05 Occurrence rates and uncertainties for small planets (eta-Earth)
SCI-06 Yield estimation for exoplanet direct imaging missions
SCI-09 Dynamical confirmation of exoplanet candidates and determination of their masses and orbits
SCI-12 Measurements of accurate transiting planet radii

Recommendation:NASA should launch WFIRST to conduct its microlensing survey of distant planets and to demonstrate the technique of coronagraphic spectroscopy on exoplanet targets.

NAS Exoplanet Science Strategy (2018)

3. Exoplanet Dynamics: Determination of Orbits and Masses

Exoplanets can be discovered and characterized through their gravitational influence on their neighbors – including their host star, other planets, and debris belts in the system. As the light from the exoplanet host stars can be observed much more easily than that of the planet, multiple methods use the star's light to infer the existence of the exoplanet and constrain its mass and orbit (semi-major axis, period, eccentricity, etc.). *Masses* and *orbits* are critical for characterizing the properties of exoplanets, and there is broad scientific interest in *planetary system architectures* - their diversity, types, and the frequency of systems like our Solar System (SAG 15) [37]. By *planetary system architecture*, we follow the SAG 15 definition: "*a descriptor of the high-level structure of a planetary system as given by the stellar mass, the orbits and mass of the planets, as well as the location and masses of its planetesimal belts*." The types of planetary architectures, and the orbital and compositional properties of their planets provide comparison for modeling efforts to understand the physical models for forming planetary systems, and ultimately the conditions for spawning potentially habitable worlds. Measurements of planet mass provide an initial *empirical* estimate of planet type and composition, although the mass obviously needs to be combined with a radius estimate to be able to calculate a model-independent or trend-independent bulk density to constrain chemical composition. When combined with stellar properties like mass and luminosity, knowledge of the orbital parameters can be used to predict stellar irradiances (both total irradiance and spectral energy distribution), which informs efforts to model the atmospheric profile and constrain the planet's temperature. Dynamical techniques for detecting and characterizing exoplanets can be generally split into *planet-star*, *planet-planet*, *planet-background star*, and *planet-disk*. The various individual methods representing these general techniques are discussed individually in the following subsections, while the latter is discussed in Sec. 4.3.

3.1. Dynamics: State of the field

Planet-star dynamical detection involves measuring the reflex motion on the star(s) due to the planet and star(s) orbiting a common center of mass. Multiple techniques have been used to detect the reflex motion on the star by the planet. By far, the most successful *dynamical* method of detecting and characterizing exoplanets has been precise measurement and monitoring of the host star's radial velocity, i.e. the *Doppler spectroscopy*, which has resulted in the discovery of over 600 exoplanets over the past three decades [38]. The oldest method of exoplanet detection is to precisely measure the position of the host star and monitor its motion with respect to neighboring stars, i.e. *astrometry* [39, 40]. Despite being employed for decades, the astrometric detection method has yet to yield a convincing exoplanet discovery that has withstood scrutiny. However, precision astrometry from space with the ESA Gaia mission is predicted to yield discovery of thousands of giant exoplanets over the coming decade [32, 40], which should renew interest in the technique. A relatively small number of exoplanets (<10 each thus far, per technique) have also been discovered via *eclipsing binary star timing variations*, *pulsar timing variations*, and *stellar pulsation variations*.

Radial velocity method (Doppler spectroscopy): The radial velocity method and its history are summarized in the review chapter by Lovis & Fischer [38]. The radial velocity amplitude of Jupiter perturbing the Sun is ~12 m/s, while that of the Earth is ~9 cm/s (currently well below the threshold for state-of-the-art). The situation is less dire for lower mass stars, where an Earth-mass planet orbiting in the habitable zone of a ~0.1 M_{Sun} red dwarf would produce an amplitude of ~1 m/s. Advancements in precision radial velocity techniques made it possible to measure velocities accurate to ~15 m/s in the 1980s. The first detections of companions to main sequence stars with inferred masses below the deuterium-burning limit (~13 M_{Jup}) that are currently counted as *exoplanets* in the NASA Exoplanet Archive[4] [41] are γ Cep b (~1.7 M_{Jup}) discovered by Campbell, Walker, & Yang in 1988 [42] followed by HD 114762 b (~11 M_{Jup}) discovered by Latham et al. in 1989 [43]. An era of discovering gas giants on close-in orbits started in the mid-1990s when two groups achieved ~3 m/s accuracy in measured radial velocities [44, 45] and within a decade over 170 exoplanets were discovered via the method [46]. Discoveries made with the radial velocity technique during the 1990s and 2000s are summarized by [38] and include: "hot Jupiters" [44, 47], the first multi-planet systems [47], giant planets on eccentric orbits [48], the first exoplanet subsequently found to transit [49], planets orbiting M dwarfs [50], planets orbiting red giants [51], sub-Neptune-mass planets [52], super-Earths [53], and the fact that the occurrence of gas giant planets was correlated with stellar metallicity [54]. The flurry of new Doppler spectroscopy discoveries launched research into simulating the formation of exoplanets and orbital migration [55, 56, 57, 58].

Astrometry: Astrometry is the oldest method for trying to detect exoplanets, however clear cases where astrometry was used to *discover* a confirmed exoplanet are lacking. Ground-based astrometry combined with space-based astrometry with the Fine Guidance Sensor (FGS) on HST has been used to constrain the orbit and mass of the candidate exoplanet orbiting ε Eridani [59], with reflex amplitude at the tenths of milliarcsecond (mas). The amplitude of the astrometric reflex motion of an Earth-mass planet at 1 au orbiting a solar mass star at 10 parsecs is 0.3 microarcseconds (μas). In order to conduct a useful survey for rocky planets in the habitable zones of Sun-like stars within 20 parsecs, one would need end-of-mission narrow angle precision of 0.05 μas [60]. Compare these values to typical accuracies achievable for measuring parallaxes from the ground (~1 mas) [61, 62] and the accuracy of wide-angle astrometric measurements tied to a system of reference sources (~20 mas) [63].

Planet-planet dynamical detection can be achieved after at least one planet in a system is detected via a planet-star dynamical detection method (usually transit method or radial velocity method). Methods that have used timing variations to detect or constrain the properties of additional planets include *transit timing variations* (TTV) and *pulsar timing* (not discussed elsewhere as we are focused on normal stars). While the transit method yields exoplanet discoveries geometrically through exoplanets blocking the light of their host stars, TTVs can be used to dynamically confirm that the transits are due to exoplanets, dynamically infer the existence of unseen planets, and dynamically estimate the exoplanet's masses [64]. TTVs have become powerful probes of the

> *"Finding: High-precision, narrow-angle astrometry could play a role in the identification and mass measurement of Earth-like planets around Sun-like stars, particularly if the radial velocity technique is ultimately limited by stellar variability."*
>
> *NAS Exoplanet Science Strategy (2018)*

[4] https://exoplanetarchive.ipac.caltech.edu/

dynamics and planet masses of transiting multi-planet systems, especially in regimes where measuring radial velocities are currently challenging (where either the velocity amplitudes are <1 m/s or the star is faint). Variations in the timing of exoplanet transits may be due to a variety of phenomena – some related to the existence of other planets, and some not. Transit timing variations may be due to periastron advancement due to relativity, oblateness, or tides, or more minor effects like tidal dissipation, tidal stripping of mass, and migration due to scattering and ejection of small bodies [65]. None of these mechanisms require the existence of another sizeable planet. However, interactions between planets near mean motion resonances can produce transit timing variations which can be used to discover and characterize (constrain the orbit and mass of) exoplanets which do not transit their star (e.g. Kepler-19 c) [66]. The power of TTVs to improve knowledge of the orbits and masses of exoplanets was recently demonstrated by long Spitzer and K2 campaigns monitoring the TRAPPIST-1 transiting multi-planet system [67], which detected timing variations at the tens of seconds to tens of minutes level, and strongly constrained the densities of all seven planets [68].

"The ultimate goal is to image rocky planets that lie in the habitable zone—at a distance from their central star where water can exist in liquid form—and to characterize their atmospheres. To prepare for this endeavor, the committee recommends a program to lay the technical and scientific foundations for a future space imaging and spectroscopy mission. NASA and NSF should support an aggressive program of ground-based high-precision radial velocity surveys of nearby stars to identify potential candidates. In the first part of the decade NASA should support competed technology development to advance multiple possible technologies for a next-decade planet imager, and should accelerate measurements of exozodiacal light levels that will determine the size and complexity of such missions."

New Worlds, New Horizons in Astronomy & Astrophysics (2010)

Planet-background star dynamical detection (*microlensing method*) is where an exoplanetary system (exoplanet and its star) or a "rogue" planet (without host star) passes in front of a background stars as seen from Earth, producing an increase in brightness due to gravitational lensing [69]. Usually, lensing by the host star produces a large increase in brightness over a period of weeks, while lensing by the exoplanet usually produces a smaller increase over a shorter time projected on to stellar lensing light curve [70]. Modeling of the light curve of the microlensing event can yield the mass ratio of the planet to the star, which can be refined if the mass of the lensed star can be observationally constrained.

3.2. Dynamics: Current and upcoming activities

Radial Velocity (Doppler Spectroscopy): In terms of the capabilities of past, present, and future precision radial velocity spectrographs, the state of the field is succinctly surveyed and summarized by [71] and the prospects for current and planned radial velocity spectrographs to address NASA science priorities is summarized in the SAG 8 report for the ExoPAG [72]. A table of planned and current visible precision radial velocity spectrometers are tabulated in Table 2 of the SAG 8 report, and the red and near-infrared spectrographs are tabulated in Table 3 of the SAG 8 report. Table 1 of [71] lists 14 active Doppler planet search programs as of early 2016, with single measurement precisions ranging from 0.8 m/s (HARPS, HARPS-N) to 5 m/s (Tull), and sample sizes ranging from a dozen to 4000. The list of current Doppler programs was limited to the range from 380-980 nm, however multiple near-infrared high precision Doppler spectrographs are in development which may push down to ~0.2 m/s (e.g. HPF, CARMENES, etc.) [71]. Spectrograph system architectures are split between slit vs. fiber input, level of environmental control, spectral resolution, wavelength range and calibration.

The NEID (NN-EXPLORE Exoplanet Investigations with Doppler spectroscopy) spectrograph will provide the community with a state-of-the-art instrument for conducting precision Doppler observations to detect exoplanets orbiting nearby stars using the WIYN 3.5-m telescope on Kitt Peak [73]. NEID is a high resolution spectrograph (R=100,000) covering the wavelength region 380 to 930 nm, with anticipated radial velocity precision of 0.29 m/s. NEID will be commissioned in 2019, time will be made available to the US community through the NOAO Time Allocation Committee. Observations will be conducted in queue mode to ensure efficient use of telescope time, and data will be archived and pipeline processed at NExScI.

While NEID is being designed to deliver ~0.3 m/s-level radial velocity precision, at the sub-m/s level the Doppler signature is dominated by noise from the star itself. Stellar jitter due to the Doppler signature of the motions of the star’s photosphere and active regions can be greater than m/s level for many stars, and sub-m/s for the least active stars. Improvement in the radial velocity method was steady between the 1980s and approximately 2010, however during the 2010s there have been few detections able to break through to the tens of cm/s level (see Figure 3). Early success in mitigating the effects of stellar activity (where it dominates “jitter”) came from correlating velocities with activity indices or statistical moments of photospheric absorption lines. More recent work has focused on using Gaussian processes to model the radial velocity signatures and separate the intrinsic stellar components of the noise from the Doppler signals of the exoplanets. At noise levels below the stellar jitter, mumerous sources of accuracy contribute to the radial velocity error budget (e.g. [38, 74]), and several terms contribute uncertainty at the tens of cm/s down to cm/s level. However the tallest pole in the error budget remains stellar jitter, and mitigation calls for more sophisticated statistical and modeling methods that will require high cadence Doppler observations of the stars for timescales longer than the orbital period of the planet and rotation period of the star [25].

While most radial velocity spectrographs have historically operated in the blue through red optical, in recent years there has been an ever-growing list of surveys operating in the near-infrared (Table 2 & 3 of [72]), however the near-IR radial velocity accuracy has typically lagged (with ~3 m/s being a typical recent level; [75, 76]). The empirical precision of radial velocity measurements as a function of wavelength region from the visual through the near-infrared is for the CARMENES survey of nearby red dwarfs in Figure 6 of [76]. Results from the CARMENES survey shows that the most sensitive band for radial velocity measurements for most M dwarf stars appears to be 0.7-0.9 μm, where ~1 m/s velocities are achievable, although near-IR radial velocities become of similar sensitivity for the very latest Ms (M8-M9V) [76]. The state of the art for the Doppler spectroscopy technique as of 2017 was the recent detection of a candidate low-mass planet in the habitable zone of the Sun’s nearest stellar neighborhood: the red dwarf Proxima Centauri [25]. The detection of Proxima Centauri b, with minimum planet mass of 1.3 M_{Earth}, orbital period of 11 days, required measuring a radial velocity amplitude of only 1.4 m/s. The detection was based on observations taken with data from five observing campaigns using two different spectrographs, with the decisive dataset being a high-cadence set of spectra taken with the HARPS spectrograph nightly over an approximately two-month span. The high cadence of the spectra was needed to disentangle the effects of stellar activity and jitter over the course of multiple planetary orbits. At present, the lowest mass planet detected via radial velocity method is GJ 273 c, a planet with *m*sin*i* of 1.2 M_{Earth} orbiting with a 4.7-day period around a nearby M dwarf [77]. The longest period exoplanet with orbital period known to better than 10% accuracy is for a giant planet with period 20 years [78], although numerous "trend" systems are known with distant perturbers [79].

Astrometry: The ESA Gaia mission launched in December 2013 and is conducting a 5-year astrometric all-sky survey of the brightest billion stars on the sky [80, 81]. Final astrometric accuracies are predicted to be ~10 µas for stars in the G magnitude range 7-12, and degrading to ~20-25 µas down to 15th magnitude [32]. Fitting to single exoplanet systems will require fitting 12-parameter astrometric models (5 covering the position, proper motion and parallax of the star, and 7 for the Keplerian parameters) to the multi-epoch data (with typical astrometric uncertainties of ~35 µas for bright stars). Predictions are that ~20,000 planets should be discovered; most of those with well-determined orbits will have periods shorter than the mission lifetime (nominally 5 years), and perhaps ~100 may be discovered around nearby M dwarfs [39]. Extending the Gaia mission to a decade would likely increase the number of exoplanets with characterized orbits to ~70,000 [32]. Current ground-based astrometric programs typically reach parallax uncertainties at the ~1 mas level [82], however reliable exoplanet detections have not been forthcoming.

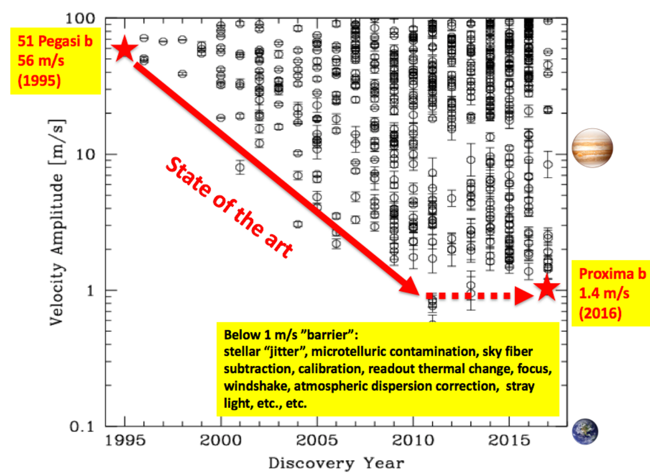

Figure 3: Radial velocity amplitudes of exoplanets detected from mid-1990s through early 2017 as a function of date, for detections at greater than 3σ significance.

3.3. Dynamics: Knowledge needed to inform ExEP Objectives

Dynamical observations are crucial to understanding the nature of exoplanet candidates. Timeseries measurements of stellar reflex motion constrain their masses, allowing them to be classified as a brown dwarf, gas giant planet, rocky planet, or background contaminant. These measurements also provide an orbital period, allowing a genuine planet's orbital semi-major axis and approximate equilibrium temperature to be derived. The Exoplanet Exploration Program seeks dynamical observations of exoplanet candidates detected by transit surveys (e.g. K2, TESS), and dynamical surveys of these and other bright suitable stars to discover and characterize their overall exoplanetary system architectures. It is particularly important to obtain these measurements for exoplanet targets amenable to atmospheric spectroscopy observations (e.g. with JWST, WFIRST-CGI).

Radial velocity and (to a lesser extent) astrometric measurements of stellar reflex motion are limited by time-varying phenomena in stellar atmospheres. These effects currently limit detectable radial velocity semi-amplitudes to ~1 m/sec, a factor of ~30 away from what is needed to detect and measure the masses of rocky planets in the habitable zones of Sun-like stars. The Exoplanet Exploration Program seeks multiple lines to attack that would improve the sensitivity of radial velocity measurements to the level of a few cm/sec for Sun-like stars. Scientific work towards this goal includes modeling the velocity fields in stellar photospheres, statistical analyses of radial velocity datasets, and obtaining and analyzing new high-cadence, high-precision datasets to guide developments in the detrending of stellar dynamic jitter. Technology work that improves spectrograph stability and calibration, along with Programmatic efforts to expand access to facilities, will also be needed.

Science Gaps in this topic area:
SCI-04 Planetary system architectures: occurrence rates for exoplanets of all sizes
SCI-08 Mitigating stellar jitter as limitation to sensitivity of dynamical methods to detect exoplanets and measure their masses and orbits
SCI-09 Dynamical confirmation of exoplanet candidates and determination of masses and orbits
SCI-10 Precursor surveys of direct imaging targets

4. Exozodiacal Dust: Exoplanet Tracer and Obscurer

Finding: The radial velocity method will continue to provide essential mass, orbit, and census information to support both transiting and directly imaged exoplanet science for the foreseeable future.

Finding: Radial velocity measurements are currently limited by variations in the stellar photosphere, instrumental stability and calibration, and spectral contamination from telluric lines. Progress will require new instruments installed on large telescopes, substantial allocations of observing time, advanced statistical methods for data analysis informed by theoretical modeling, and collaboration between observers, instrument builders, stellar astrophysicists, heliophysicists, and statisticians.

Recommendation: NASA and NSF should establish a strategic initiative in extremely precise radial velocities (EPRVs) to develop methods and facilities for measuring the masses of temperate terrestrial planets orbiting Sun-like stars."

NAS Exoplanet Science Strategy (2018)

If habitable planets orbiting nearby stars represent the metaphoric "new worlds" of this century's explorers, then exozodiacal dust disks are the figurative shoals, sandbars, and reefs in this quest. To be clear, the main concern from the perspective of achieving the long-term goals of imaging and spectroscopically studying exo-Earths orbiting nearby stars is with *warm exozodiacal dust disks* orbiting in the vicinity of habitable zones. Dust disks like the solar system's zodiacal dust represent 2nd generation dust produced from the collisions or sublimation of planetesimals (asteroids, comets). Collisions grind down these grains to sizes small enough where radiation pressure and Poynting-Robertson drag effects either blow them out or drag them towards the star, respectively, on timescales much shorter than the star's lifetime [83, 84].

Exozodiacal dust disks are a duel-edged scientific *opportunity* and *risk*. Exozodis comprise a *risk* in that they constitute a source of optical and infrared background emission which could hamper efforts to directly image small exoplanets orbiting nearby stars using future space-based telescopes. Exozodis provide a scientific *opportunity* as they trace interplanetary dust grain populations that indicate the existence of debris belts (reservoir of solids analogous to our solar system's asteroid belt). The clumpiness and characteristics of exozodiacal disks can lead to dynamical inferences to the existence of smaller planets, and constraints on their masses and orbits.

Cold exozodiacal dust disks well beyond stellar habitable zones, generated by collisions in analogues of the solar system's Kuiper Belt (typically at tens of au), are also interesting signposts of exoplanets, however they are of less practical concern for imaging of exo-Earths. Gas-rich *protoplanetary disks* are interesting in their own right as laboratories for studying the chemical and physical processes under which planets form. However, these type of disks are constrained to the first millions of years of stellar life, and are very rare in the solar vicinity (none known within 30 pc, only a few associated with ~10 Myr-old stars within 60 pc). Given their importance to the study of exo-Earths around nearby (old) field stars, we concentrate our discussion on the phenomena of *warm exozodiacal dust disks* in the vicinity of habitable zones around nearby field stars, at the exclusion of *cold exozodiacal dust disks* and *protoplanetary disks*.

After the central star and its orbiting planets, small bodies and their dusty debris comprise the third component of extrasolar systems. These are the remnant objects from planet formation such as our solar system's asteroid and Kuiper belts, comets, and zodiacal light. While individual small bodies are undetectable at interstellar distances, their mutual collisions and sublimation continually maintains a population of tiny dust grains that can be observed as thermal excess emission above the stellar photosphere and as circumstellar disks seen in resolved images. In some cases small body populations can also produce absorption features superposed on stellar photospheric spectra. Studies of dust disks provide many insights into other planetary

> *"A critical step along the way is a better understanding of the dusty disks surrounding stars, analogous to zodiacal dust found near Earth. Reflected diffuse exozodiacal light from these disks can make detection of the faint light from small Earth-like planets difficult. It is, therefore, important to quantify the prevalence and character of these dusty "debris" disks, and the period 2010-2015 will see the completion of ground-based mid-infrared interferometric instrumentation designed to study these phenomena."*
>
> *New Worlds, New Horizons in Astronomy & Astrophysics (2010)*

systems. The locations of the dust relative to planets and volatile condensation horizons is of intrinsic interest to understanding the processes of planet formation and asteroidal collisions. As in planetary rings, the detailed structure of a circumstellar dust disk can show clues to the presence and properties of adjacent perturbing planets. The dust grain size and composition can often be inferred from colors or spectral features, directly informing us on the composition of exosolar asteroids and comets. Finally, exozodiacal dust in the habitable zone - or merely projected across the habitable zone in inclined systems - can produce a bright background light that hinders the detection of habitable planets and their potential for hosting life. For all these reasons, a full understanding of exosolar systems must include understanding their populations of small bodies and exozodiacal dust.

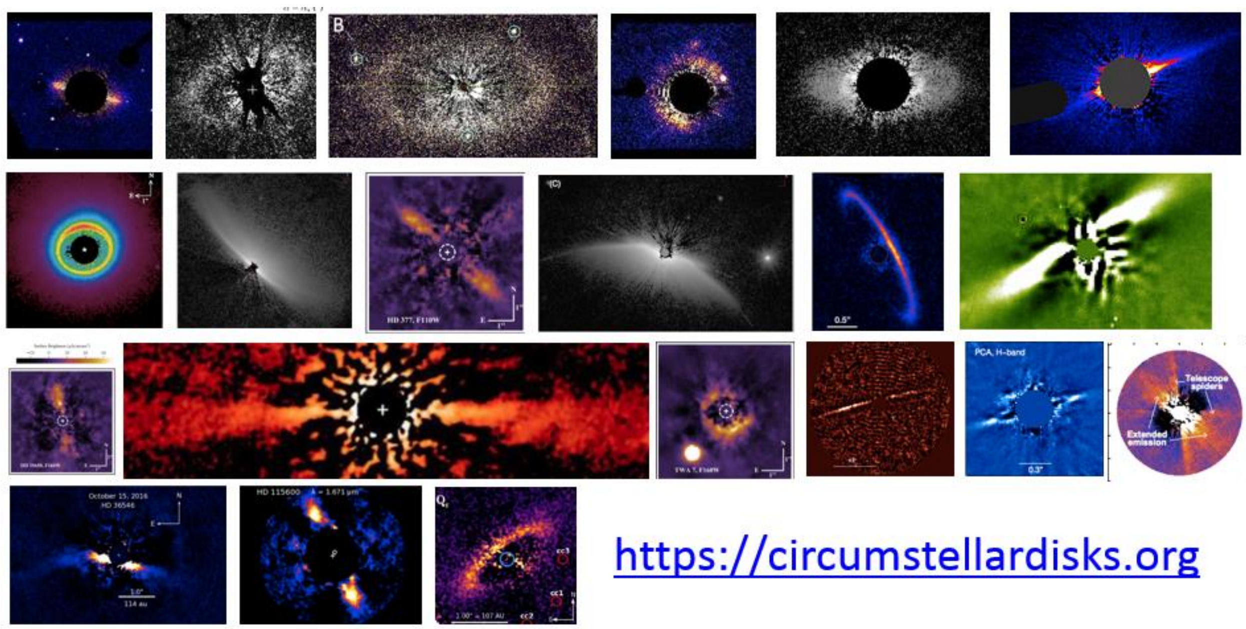

Figure 4. Debris disks imaged in scattered light using HST, the VLT, and GPI. From the compilation at the online catalog of resolved disks. These objects are typically 100 AU in radius. No images of warm HZ dust are available to date.

4.1. Exozodiacal Dust: State of the field

The first dust disks were discovered by the IRAS satellite [85, 86] and seen mostly around luminous A-type stars. Spectroscopy by the 1995 ISO mission showed that the dust particles were ordinary silicates with composition very similar to solar system comets [87]. The advent of adaptive optics, coronagraphy with the repaired HST, and sensitive submillimeter observatories has allowed numerous debris disks to be spatially resolved. From these observations it is clear that most debris disks are tens to hundreds of AU in size, analogous to our solar system's Kuiper Belt [83]. Disk images show central holes, warped midplanes, eccentric rings, and perhaps resonant clumps that require planetary perturbations [88, 89]. The Spitzer and Herschel missions surveyed large stellar samples, finding that infrared excess from disks is present around 15-20% of solar-type stars, is brighter/dustier around younger stellar hosts, is largely absent around red dwarf stars, and that circumbinary debris disks exist [90, 91]. Most debris disks have characteristic temperatures of ~50 K, with a smaller population of disks warmer than 150 K [92]. Habitable zone dust (T ~ 300 K) is difficult to measure from infrared excess alone: the relatively bright stellar photospheres at 10 μm wavelength limits detections to a small sample of very dusty stars. Nulling interferometry at Keck provided an upper limit of 90 times the solar system dust levels for the habitable zones of nearby stars [93]. Even hotter dust with temperatures near 1500 K has been detected in some nearby systems using near-infrared interferometry. This hot dust population does not correlate with the presence of excess at other wavelengths and thus is not fully understood [94]. No correlation is seen between debris disks and planets detected by the radial velocity method, probably because the two are spatially widely separated in most systems. However, the small number of directly-imaged, wide-separation planets is preferentially found in association with young debris disk systems. To advance the theory of disk-planet interactions, it would be greatly helpful to identify and study more examples where both exoplanets and disks are imaged in the same system.

4.2. Exozodiacal Dust: Current and upcoming activities

Scattered light observations of debris disks have recently surged with discoveries in archival HST data and the advent of new extreme adaptive optics systems on large ground-based telescopes. HST observations generally have better sensitivity to the low surface brightness regions of the outer disk, while the ground AO systems provide better inner working angles and smaller fields of view. Experience shows that both are limited to detections of disks 100-1000 times dustier than the Kuiper Belt (or fractional luminosities $\geq 10^{-4}$), and detections outside $\geq$ 10 AU separations [95]. More than 2 dozen debris disks are now well-imaged in scattered light, while many other dusty disks remain undetected due to some combination of dark grains, the lack of sharp spatial features, or face-on orientation. Time-variable disk structure has been observed for the first time in the case of AU Mic [96], possibly due to stellar flaring activity. HST and ground AO should continue to make progress over the next few years with new disk detections, multi-wavelength modeling, and studies of dust properties from polarimetry. The Atacama Large Millimeter Array (ALMA) is the penultimate instrument for imaging of protoplanetary disks. Debris disks have far less dust and much weaker submillimeter fluxes, and thus are difficult for ALMA to study at sub-arcsecond resolution. Work to date has been a mixture of quick-look detections in samples of young debris disks, and more detailed studies of a few keystone systems [97]. Results to date have shown that submillimeter emission tracing large grains is more spatially confined that the scattered light distribution that traces small grains. This behavior is understood as the effect of radiative forces moving small grains away from their parent body regions. ALMA has yet to detect sub-mm emission from warm inner dust belts, as the signals are blended with the star and difficult to distinguish from non-thermal excess emission originating from stellar winds. The number of debris disks mapped with ALMA can be expected to increase significantly over the next few years, complementing ALMA's exceptional work on protoplanetary disks.

Ground-based interferometry continues to be employed in the study of hot dust, with both the Very Large Telescope Interferometer (VLTI) and CHARA array monitoring known excess systems and expanding their samples of surveyed targets [98]. Theoretical work will hopefully lead to a firm interpretation for the origin of the hot dust. Among the possibilities are magnetically-trapped populations of nanometer-sized grains and transient grain populations from the disruption of stargrazing comets. There is as yet no indication that the presence of this hot dust has implications for dust levels in the habitable zone. Direct measurements of HZ dust have been made by the Large Binocular Telescope Interferometer (LBTI), which nulls out the central star to detect excess extended emission at or below 0.1% of the stellar photosphere [99]. As of this writing the LBTI HOSTS exozodi survey has completed with observations of 38 stars. Interim results [100] find 10 μm excess in 1/6th of the targets, and place a preliminary 95% confidence upper limit of 26 zodis for the median exozodi level around Sun-like stars. Analysis of the full data set will continue through 2019, with final statistical results for habitable zone dust levels available by the end of that year. The HOSTS survey result is the most definitive measurement of the exozodiacal backgrounds of nearby stars that will be available to the 2020 Decadal Survey of Astronomy & Astrophysics [101].

Beginning in 2021 the James Webb Space Telescope will offer new capabilities for debris disk imaging and spectroscopy. Sensitive mid-infrared imaging from outside the atmosphere will resolve the warm dust belts of nearby luminous stars such as Vega and Fomalhaut, but any warm dust around sun-like stars will not generally be extended enough to resolve. The mid-infrared disk images realized by JWST/MIRI will probe disk structures in a new domain of dust temperature and dynamics. MIRI spectroscopy could measure dust grain properties in stars newly shown to have HZ dust by the WISE all-sky survey. In the near-infrared, the contrast provided by JWST coronagraphs will not be any better than what HST has already achieved. As a result, JWST's main contribution to scattered light imaging will be to extend the wavelength range for known disks across the 3 μm water band and out to 5 μm. In combination with images at shorter wavelengths, these results will provide information on dust grain sizes and compositions in cold debris disks [102].

The first coronagraph with precision wavefront control is expected to fly as a technology demonstration instrument on the WFIRST mission in the mid-2020s. Operating in visible light, the "CGI" instrument is expected to achieve contrasts 2-3 orders of magnitude better than HST 0.2-1.0 arcseconds from bright stars [103]. This capability should enable imaging of more tenuous debris disks where Poynting-Robertson drag dominates over collisional removal of grains. Good target systems to image have already been identified by the Spitzer, Herschel, and WISE far-infrared surveys. With its increased sensitivity, CGI should enable imaging of dozens of new cold debris disks and thus the opportunity to detect disk structures driven by the perturbations of outer planets. For a couple dozen nearby stars, CGI's inner working angle will permit observations into habitable zones and the possible detection of warm exozodiacal dust in reflected light. Specific sensitivity levels are still being determined. The detection of warm dust in both scattered light with WFIRST and thermal emission with LBTI would allow the first determination of dust albedoes in the habitable zones of other stars.

"Astronomers are now ready to embark on the next stage in the quest for life beyond the solar system—to search for nearby, habitable, rocky or terrestrial planets with liquid water and oxygen. The host star of such a planet may be one like our Sun, or it could be one of the more plentiful but less hospitable cooler red stars. Cooler red stars are attractive targets for planet searches because light from a planet will be more easily detected above the stellar background. Making the search harder, terrestrial planets are relatively small and dim, and are easily lost in the exozodiacal light that is scattered by the dusty disks that typically orbit stars. The observational challenge is great, but armed with new technologies and advances in understanding of the architectures of nearby planetary systems, astronomers are poised to rise to it."

New Worlds, New Horizons in Astronomy & Astrophysics (2010)

4.3. Exozodiacal Dust: Knowledge needed to inform ExEP Objectives

Habitable zone dust will impede future efforts to directly image and characterize habitable exoplanets [101]. The severity of the problem depends on the spatial resolution of the telescope to be used and the maximum distance of the stellar targets to be explored. To inform a range of possible mission architectures, the Exoplanet Exploration Program seeks measurements of habitable zone dust content and reflected light surface brightness for Sun-like stars, down to a sensitivity level of a few times the level in our solar system. This is needed across a general statistical sample, and ideally also for the specific stars to be targeted by a future exoplanet direct imaging mission.

Dusty debris and its parent body belts are part of the overall architectures of exosolar systems. In order to assess the system context for giant planets, habitable planets, and life, the Exoplanet Exploration Program seeks to understand the location, density, extent, sources, and sinks of circumstellar dust orbiting nearby stars, and to compare them with the asteroid and Kuiper belts in our own solar system. Exploration of these properties across a range of stellar types and ages is desirable.

Dusty debris provides a large population of test particles orbiting a star under the influence of its gravitational and radiative forces. An exoplanet's gravity can also perturb this dust, producing disk structural features diagnostic of the planet's mass and orbital elements. Some very small planets, or cold planets on very long period orbits, may only be detectable through their perturbations on debris dust. The Exoplanet Exploration Program seeks observational progress in the discovery of disk structures indicating the presence of planets, and theoretical progress in inverting these structures to characterize the perturbers, towards the goals of characterizing the full range of planetary bodies in an extrasolar system and the extent to which perturbed dust structures could be confused with habitable planets.

Science Gap in this topic area:
SCI-11 Understanding the abundance and distribution of exozodiacal dust

5. Properties of Target Stars

Accurate knowledge about stars in exoplanet surveys impacts all three of ExEP's broad science goals: the discovery of planets around other stars (as survey targets), characterizing their properties, and identifying candidates that could harbor life (as exoplanet host stars). As astronomers progress from planning campaigns to *discover* exoplanets to planning follow-up observations to improve *characterization* of exoplanets, and to assessing *habitability*, one progresses from needing *approximate* to *precise* knowledge about stars in order to improve knowledge about their exoplanets. Modeling planetary atmospheres and their evolution certainly requires accurate knowledge of host star properties and the ability to predict the star's properties as a function of stellar age.

Exoplanet program science is advanced by improving knowledge of what can generally be called "*stellar properties*". *Stellar properties* can be broken down to *intrinsic* stellar properties ("stellar parameters") and *extrinsic* stellar properties ("stellar environment"). *Intrinsic* stellar properties cover measurements of e.g. stellar radius, effective temperature, luminosity, spectral energy distribution, mass, chemical composition, age, rotation, parameters related to magnetic activity, distance, velocity, etc. *Extrinsic* stellar properties are related to knowledge of the vicinity of the exoplanet and its host star – properties which may be important for target selection, assessing the prospects for habitability, and de-biasing measurements of stellar and exoplanet parameters. Examples of *extrinsic* stellar properties are knowledge of the other exoplanets and dusty debris belts in the system (e.g. Sec 4.3 on exozodiacal dust), knowledge of physical stellar companions (and their basic intrinsic and orbital properties), and knowledge of unrelated background or foreground stars which may affect interpretation of measurements related to the exoplanet and its host star.

Planning survey strategies for discovering and characterizing exoplanets requires some prior knowledge of the star's characteristics. Often, detailed investigation of the star's properties and multiplicity (requiring access to instruments on telescopes other than the facility that initially discovered the exoplanet) are planned after the discovery. The importance of prior knowledge of accurate stellar characteristics is greater when considering planning mission surveys, and when mission lifetime and consumables factor into mission design (e.g. cryogen, starshade fuel, spacecraft orientation with regard to communications and solar power, limited bandwidth for transmitting portions of detector data, etc.).

5.1. Target Stars: State of the field

The importance of accurately characterizing the properties of target stars (for discovery surveys) or exoplanet host stars (for follow-up surveys) is apparent for all exoplanet survey activities. Estimating accurate exoplanet radii via the transit method requires accurate estimates of stellar *radii*, and knowledge of the intrinsic stellar properties and other stars in the vicinity (including physical companions and unrelated interlopers).

> *"Finding: Understanding of exoplanets is limited by measurements of the properties of the parent stars, including mass, radius, distance, binarity, rotation period, age, composition, emergent spectrum, and variability."*
>
> *NAS Exoplanet Science Strategy (2018)*

Estimating the masses, orbital separations, and temperatures of exoplanets detected via the radial velocity method requires knowledge of the star's *mass*, and measures of the star's magnetic activity may inform the level of anticipated radial velocity "jitter". Estimating masses of self-luminous exoplanets imaged at wide separations around stars requires constraints on the star's *age*. Valuable observing time on future flagship missions capable of imaging exo-Earths around nearby stars could be lost if the target stars are not properly vetted for stellar companions, stellar age, and exozodiacal dust emission, etc. Planetary scientists and astrobiologists working to physically model exoplanets will want to not only know the exoplanet's parameters quite accurately (e.g. orbital radius, mass, radius, etc.) but the host star's parameters as well (e.g. chemical composition, bolometric luminosity, X-ray/UV/optical/infrared spectrum, age, stellar mass loss rates, flaring properties; e.g. SAG 15 report [37]). Studying ensembles of hundreds or thousands of exoplanets and their host stars, astronomers can start to extract statistical trends in planet and star properties that provide important clues to formation mechanisms, evolutionary pathways, and disentangling planetary types relevant to issues of habitability [15, 12].

Estimating accurate radii of exoplanets via the transit method requires accurate stellar radii. While some nearby and bright stars have directly measured angular radii (which can be combined with distance to estimate physical radius [104]), radii are usually estimated either by combining estimates of bolometric luminosity and effective temperature, which themselves require accurate broadband photometry, spectroscopy, and distances [105]. If distances are not available, then combining accurate photometry and estimates of stellar parameters (e.g. effective temperature, metallicity, surface gravity, etc.) from high-resolution spectroscopy can be combined with theoretical stellar evolutionary tracks to predicted stellar radii, masses, and ages [106]. As transit studies often use large pixels which can lead to light from multiple stars contributing to the light curves, it is important to assess the existence and approximate properties of stars in the immediate vicinity – whether physical companions or interlopers.

A summary of relevant stellar and exoplanetary parameters is illustrated in Figure 5, which comes from the recent Spitzer study of the TRAPPIST-1 multiplanet system by [67]. The planet radii are calculated from combining information from the transit light curve (giving the ratio of the radii of the exoplanets and their host star) and the star's radius, which is calculated via the estimated luminosity and effective temperature. Knowledge of the stellar parameters, combined with FUV spectroscopy using HST/STIS and X-ray imagery using XMM-Newton, have been recently used to constrain the high energy irradiation of the planets by the star TRAPPIST-1 and estimate their atmospheric loss through photodissociation [107].

5.2. Target Stars: Current and upcoming activities

Improved characterization of stellar targets improves our knowledge about exoplanet candidates already identified from prior work (e.g. Kepler, K2, ground-based transit and RV surveys, direct imaging, etc.) and new candidates being studied by current and upcoming missions (e.g. TESS, JWST, future mission concepts). Improving knowledge of stellar spectral energy distributions (SEDs), high energy photon emission (e.g. X-ray, ultraviolet), and particle fluences can help with modeling planetary atmospheres and spectra, evolution of those atmospheres and planetary surfaces, and assessments of habitability. We discuss some efforts to improve characterization of target stars for various types of exoplanet surveys.

Input Catalogs for Transit Surveys with Space Observatories (e.g. Kepler, K2, TESS): Space observatories using the transit method to discover and characterize exoplanets require input star catalogs capable of providing accurate effective temperatures, stellar radii, and effective segregation of dwarf vs. giant stars. Recent examples include the Kepler Input Catalog (KIC; [108, 109]), K2 Ecliptic Plane Input Catalog (EPIC; [110]), and TESS Input Catalog and Candidate Target List (TIC & CTL; [111]). Given the sensitivity of the transit technique to small radii planets orbiting small stars, a premium has been placed on characterizing the brightest and nearest, small, cool dwarf stars (e.g. [111, 112]). Photometric and astrometric sky surveys have made production of large input catalogs possible, however the historical lack of trigonometric parallaxes for most faint stars, difficulty in accurately assessing interstellar reddening and extinction, lead to initial estimates of stellar parameters that have large uncertainties [105, 110]. A recent example of constructing combining published photometric (optical-infrared), astrometric, and spectroscopic catalogs into an input catalog for a mission is the TESS Input Catalog (TIC; [111, 113]). The TIC is based on the 2MASS Point Source Catalog cross-matched the Gaia DR1, LAMOST-DR1 and DR3 catalogs, KIC, EPIC, RAVE DR4 and DR5, APOGEE-1 and 2, UCAC4 and UCAC5, Tycho-2, APASS-DR9, HSOY, Superblink, HERMES-TESS DR1, SPOCS, Geneva-Copenhagen, Gaia-ESO, ALLWISE, Sloan Digital Sky Survey (SDSS), Hipparcos, and other specially curated lists of special targets (described in detail in [111], and references therein). Synthesizing the TIC catalog of 470 million point sources required considerable care with regard to sources that are blended in some catalogs but resolved as multiple objects in others, extended sources, and confusion caused by artifacts. From the TIC a smaller catalog was constructed – the TESS Candidate Target List (CTL) – which provides ~200k dwarf stars for 2-minute cadence observations which will fulfill TESS's primary mission science related to searching for close-in, small transiting exoplanets [114]. While Gaia DR1 was incorporated into the TIC and CTL, the Gaia DR2 catalog, which was released in mid-2018, contained accurate parallaxes and proper motions for millions of stars, and new photometry in three optical bands. Incorporating data from the Gaia DR2, and future releases, will contribute to large-scale refinement of input catalogs like TIC.

High Resolution Imaging for Validation and Characterization of Transiting Planets Discovered with Space Observatories: High resolution imaging of candidate exoplanet host stars is useful for several purposes related to the validation and characterization of exoplanets. Approximately half of exoplanet host stars are in systems with bound stellar components (e.g. [115]). Stellar contamination by either physical stellar (or substellar) companions or unrelated interloper stars can lead to high fractions of false positive exoplanet detections, and systematic underestimation of transiting exoplanet radii [116, 117, 115]. Follow-up imaging taken with speckle imaging, adaptive optics systems (including Robo-AO), lucky imaging, seeing-limited images, and Hubble Space Telescope, etc. have recently contributed to improving assessments of stellar multiplicity and improved radii estimates of transiting planets (e.g. [116]). It has been estimated that nearly half of all Kepler exoplanet candidates could have their radii underestimated by ~65% *on average*, in the absence of high resolution imaging follow-up observations to further vet the host stars (e.g. [115]). Validation and characterization of transiting exoplanet candidates with high resolution imaging are also important for improving occurrence rate estimates, improving exoplanet irradiance estimates (and assessing whether an exoplanet lies in the habitable zone), and discovery of companions which may be responsible for radial velocity trends. NASA ExEP is currently supporting a program by Steve Howell (NASA/Ames) and collaborators to provide community access (via the NOAO time allocation process) to speckle imagers on WIYN, Gemini-N, and Gemini-S [118, 119], and data analysis support, to enable efficient vetting of Kepler, K2, and TESS targets. These observations can observe dozens of targets in a single night, and effectively contribute to the validation of exoplanet candidates and improving estimates of their radii and other parameters. Speckle images and final data products are provided to the community via the ExoFOP (Exoplanet Follow-Up Observing Program) website hosted by NExScI[5].

Spectroscopic Characterization of Exoplanet Survey Targets and Exoplanet Host Stars: Spectroscopy, especially high-resolution optical or near-infrared spectroscopy, can provide refined estimates of effective temperatures, surface gravities, elemental chemical abundances, projected rotational velocities, and various indicators of stellar age (e.g. chromospheric activity indicators like Ca H & K, abundances of elements with strong age-abundance correlations, e.g. Li, Ba, etc.). Spectroscopic assessment of these parameters is critical as photometry alone can only provide coarse constraints (see e.g. KIC), and there is considerable degeneracy in inferred parameters when one or more of the parameters (including also interstellar reddening and extinction), is not well constrained.

Useful high resolution spectra may come from a mix of sources: 1) wide-field multi-object spectroscopic surveys of target stars, 2) follow-up spectroscopic surveys of exoplanet host stars, and 3) archives (e.g. HIRES spectra from Keck Archive). Spectroscopic surveys of target stars which have measured stellar parameters like effective temperature, surface gravity, metallicity, etc. have been undertaken, are underway, and being planned (e.g. APOGEE, RAVE, LAMOST, TESS-HERMES, SDSS-V; e.g. [120, 121, 122]). Historically, however, spectroscopic surveys cover limited swaths of sky, and their coverage for the K2 fields was <10%. The new SDSS-V Milky Way Mapper (MWM) survey is planning to conduct over the 5-yr period 2020-2025 a multi-object near-infrared spectroscopic surveys with APOGEE [123] of all TESS short-cadence targets in the Continuous Viewing Zones (CVZs) with H magnitude brighter than 13.3 (1 to 8 epochs for each target star). SDSS-V MWM is also planning on taking two epochs of high-resolution H-band spectra for all stars in the solar neighborhood with Gaia parallaxes placing them within 100 pc (G < 20 and H < 12 magnitudes; ~400k targets), providing estimates of stellar effective temperature and chemical abundances for many stars which will be part of both space- (e.g. TESS) and ground-based transit surveys [122].

In the short-term, high resolution spectroscopy of host stars of exoplanet candidates discovered with space, both for stellar characterization and radial velocity follow-up, requires community access to telescopes with spectrographs (e.g. NASA Keck time and access to HIRES and eventually KPF, NN-Explore/NEID on WIYN and CHIRON on the SMARTS 1.5-m, and other instruments accessible via national and institutional observatories).

Target Stars for Direct Imaging Surveys with Space Observatories (WFIRST/CGI): The WFIRST STDTs are still defining mission science and science requirements for the WFIRST mission at the time of writing. Given WFIRST's projected contrast limits, it is expected to be able to image and

[5] https://exofop.ipac.caltech.edu/

spectrally characterize some large radii planets, and perhaps some sub-Neptune-sized planets, orbiting very nearby stars. Past ground-based precision radial velocity surveys have provide roughly a dozen exoplanet candidates that WFIRST may be able to image and spectrally characterize [124]. Their orbits should continue to be monitored for the foreseeable future with precision radial velocity instruments (e.g. NN-Explore/NEID, Keck HIRES or KPF, etc.), both to refine the orbits and masses of the exoplanets to be imaged, and search for additional trends which may yield other wide-orbit large planets [125]. Multi-epoch imaging of these planets with WFIRST may help constrain inclination, which may help constrain their masses rather than minimum masses ($m\sin i$), however practically this may only produce accurate masses (<10-20%) for a very small number of nearby systems [126]. WFIRST direct imaging targets will likely mostly be nearby bright stars, which tend to be well-characterized, and usually multiple surveys will have already provided detailed estimates of parameters like effective temperature, individual chemical abundances, etc. [127, 128, 129]. However, improved knowledge of these stars may come from e.g. more precise measurements of stellar parameters from higher resolution, higher SNR spectra, asteroseismology studies, and detailed comparison of combinations of observational parameters to evolutionary models (resulting in improved stellar ages and masses).

Target Stars for Microlensing Surveys with Space Observatories (e.g. WFIRST/WFI): The WFIRST microlensing survey will statistically assess the frequency of distribution of exoplanets by mass (down to approximately the mass of Ganymede) and orbital separation in the outer parts of exoplanetary systems, as well as assess the population of free-floating "rogue" planets [29]. The survey will be directed towards high stellar density fields in the Galactic bulge. The ExoPAG SAG 11 report [130] discusses science programs that would decrease the mission's scientific risk and enhance science yield. As the microlensing event is produced when the exoplanet and its host star passes in front of a background star, both the lensed star and background star will be close together at the time of the lensing event. Their differences in proper motion will result in the two stars slowly separating over time. Precursor imaging from space with HST in the near future can provide the spatial resolution and depth at epochs approximately a decade in advance of the WFIRST microlensing survey. Early epoch imaging would provide value astrometry for directly calculating the relative proper motion between background stars and lensed stars, improving the fidelity of fits to the lensing event. The stellar populations towards the bulge fields and the near-IR microlensing event rate should also be studied in order to optimize the choice of microlensing survey field, improve characterization of the intervening stellar population, and improve predictions for the exoplanet yield. Precursor observations of bulge fields and coordinated observing campaigns to discover and characterize microlensing events will also help develop professional expertise in this new and growing astronomical sub-field. Assessment of the improvement in target star characterization from inclusion of Gaia data for WFIRST microlensing survey efforts has not yet been assessed (or at least not published to date). Data from WFIRST itself should be able to constrain the distance and mass for the exoplanet host stars to <10% for most systems [29].

Targets Stars for Precision Radial Velocity Surveys for Exoplanets (e.g. NN-Explore/NEID on WIYN, Keck Single-Aperture): Target selection for surveys with NASA-supported precision radial velocity spectrographs stem from community proposals to time allocation committees. At present and in the near future, it is likely that most targets for precision radial velocity surveys will be dominated by 1) candidates from Kepler/K2 and TESS, and 2) nearby and bright samples of stars, including the nearest targets which will be desirable targets for direct imaging surveys for exoplanets with WFIRST. Improvements to transit survey input catalogs, and via spectroscopic and high-resolution imaging, have already been previously.

High Energy Emission for Exoplanet Host Stars: The high energy emission[6] from host stars, especially in the ultraviolet, provides important input for modeling planetary atmospheres, their spectra, and their evolution. Stellar far-ultraviolet (FUV; $912 < \lambda < 1700$ Å) and near-ultraviolet (NUV; $1700 < \lambda < 4000$ Å) emission drive chemistry in planetary atmospheres via photoexcitation and photodissociation. FUV and NUV emission also drive oxygen chemistry in planetary atmospheres, impacing the interpretation of biosignatures gases like O_2 and O_3). Extreme ultraviolet (EUV; $100 < \lambda < 912$ Å) emission may be a dominant driver of the loss of H/He envelopes through heating and ionization, perhaps transforming "sub-Neptunes" into water- or rock-dominated "super-Earths" [16, 131]. Unfortunately EUV observations are scarce for stars other the our Sun, limited mostly to the very nearest and most chromospherically active stars, due to the high absorption cross section of atomic hydrogen in the interstellar medium, especially in the region between around 400 Å and the Lyman limit (912 Å). Calculations of mass loss through photoevaporation often also include X-ray emission ($1 < \lambda < 100$ Å), readily observed as a measure of coronal activity via X-ray observatories like Chandra and XMM. Efforts to construct the X-ray and UV emission history for the Sun and solar-type stars using solar proxies have been made (with data from e.g. ASCA, ROSAT, EUVE, FUSE, HST, IUE, etc.; [132]). In practive, the EUV parts of the spectra of exoplanet host stars are modeled, using constraints on the fluences in the observed X-ray and ultraviolet bands (including the prominent H I Lyman α 1216 Å emission line observed with the HST STIS and COS spectrographs [133]). Recent work by the MUSCLES (Measurements of the Ultraviolet Spectral Characteristics of Low-mass Exoplanetary Systems) survey [133] has been employing observations spanning X-rays, UV, through the optical and infrared to construct nearly complete spectral energy distributions of low-mass (K/M-type) exoplanet host stars. The HAZMAT (Habitable Zones and M dwarf Activity across Time) program has been combining UV and X-ray observations from HST, GALEX, and ROSAT of M and K dwarfs of a wide range of ages to constrain their temporal evolution, in order to improve models of planet atmospheric evaporation [134, 135, 136]. For the present and near future, the counts of small planets in habitable zones accessible to spectroscopic observations (e.g. HST, JWST) will be dominated by those orbiting low-mass stars (mostly M dwarfs). In order to model the atmospheres of planets and understand their evolution, and aid in the interpretation of spectra (including biosignature gases), observations and modeling of the temporally and spectrally resolved UV emission (including variability and flares) for exoplanet host stars of different types and ages is needed [3]. Observations with HST should continue to provide important constraints on NUV and FUV spectral energy distributions and variability. Upcoming CubeSat missions such as the Colorado Ultraviolet Transit Experiment (CUTE; [137]) and the Star-Planet Activity Research Cubesat (SPARCS; [138]) promise to provide UV observations of transiting hot Jupiter host stars and nearby active and inactive M dwarfs, respectively [3].

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[66] The X-ray and extreme ultraviolet (EUV) range as a whole ($1 < \lambda < 912$ Å), important for modeling photoevaporation and structure of planetary atmospheres, is sometimes considered "XUV" (e.g. [196, 197, 133]), not to be confused with "EUV" (covering the extreme ultraviolet alone).

Broad Impact of the ESA Gaia Mission on Improving Stellar Characterization Across Exoplanet Surveys: The ESA Gaia mission has recently provided a quantum leap in increasing our knowledge of the intrinsic and extrinsic properties of many stars which will be the targets for exoplanet discovery and characterization with ongoing and future NASA missions. The astrometric properties of Gaia relevant to exoplanets are highlighted in Sec. 3.2, and we highlight some other important data products from Gaia here. Future Gaia Data Releases in the coming years promise to bring additional improvements that will bear on stellar characterization. Gaia will survey the entire sky over its 5-year lifetime, observing the brightest billion stars, providing precise absolute astrometry, low-resolution spectrophotometry, and photometry in multiple visible bands (*G*, *Bp*, *Rp*) [80, 81]. Gaia will also measure medium-resolution (R=11,500) spectra for ~150 million stars brighter than 17th magnitude, providing approximate spectroscopic estimates of stellar parameters (most of which have never been characterized via spectroscopy). Gaia will measure trigonometric parallaxes accurate to ~10 μas for bright stars (~6th to 12th magnitude), with decreasing accuracy down to 20th magnitude (~300 μas accuracy). Dedicated efforts are planned for separately analyzing the brightest Gaia stars (2nd to 6th magnitude), however the exact level of expected accuracy as function of magnitude is unclear [139]. Note that ground-based astrometric surveys will continue to be useful for stars and brown dwarfs fainter than the Gaia photometric limit, especially in measuring distances and velocities of ultracool dwarfs, long-term astrometric searches for exoplanet companions around the nearest cool dwarfs, and measuring dynamical masses for substellar objects which helps inform exoplanet atmosphere models [140, 141].

5.3. Target Stars: Knowledge needed to inform ExEP Objectives

Characterization of the host star is essential to understanding the properties of an exoplanet and its environment. Exoplanet sizes and masses are measured relative to the host star's by the transit and RV techniques; the host star's luminosity determines an exoplanet's thermal state, and the age of an exoplanet is virtually the same as its host's. The Exoplanet Exploration Program seeks observational determinations of the luminosity, effective temperature, stellar activity, age, high energy radiation environment, presence of companions, and circumstellar dust populations for the host stars of known exoplanets, and for the nearby stars that are viable targets for future direct imaging studies of habitable exoplanets. Significant parts of this work can be accomplished with existing ground and space facilities through normal TAC processes, provided that funding support for data analysis is made available.

Ideally stellar data would be compiled in a maintained database of published stellar parameters for

> *"Finding: Stellar UV emission impacts planetary habitability as well as the interpretation of putative atmospheric biosignature gases.*
>
> *Finding: Once HST ceases operation, researchers will essentially lose the ability to gather UV spectra of exoplanet host stars, which will limit the ability to interpret spectra of the planetary atmospheres and understand their habitability."*
>
> *NAS Exoplanet Science Strategy (2018)*

the nearby star targets of a future direct imaging mission, in a database analogous to what the

> *"Locating another Earth-like planet that is close enough for detailed study is a major challenge, requiring many steps and choices along the way. The optimum strategy depends strongly on the fraction of stars with Earth-like planets orbiting them. If the fraction is close to 100 percent, then astronomers will not need to look far to find an Earth-like planet, but if Earth-like planets are rare, then a much larger search extending to more distant stars will be necessary. With this information in hand, ambitious planning can begin to find, image, and study the atmospheres of those Earth-like planets that are closest to our own. Equally important to the characterization of an Earth-like planet is to understand such planets as a class. Although our own solar system has four such terrestrial bodies, the frequency of formation of terrestrial planets, mass distributions as a function of stellar mass, and orbital arrangements are not understood. Generating a census of Earth-like or terrestrial planets is the essential first step toward determining whether our own home world is a commonplace or rare outcome of planet formation."*
>
> *New Worlds, New Horizons in Astronomy & Astrophysics (2010)*

NASA Exoplanet Archive is pursuing for known exoplanet host stars[7]. While partial catalogs of nearby stars and their properties exist (e.g. ExoCAT, Gliese catalog, RECONS, Geneva-Copenhagen), many are static, do not have complete censuses of objects, and are not comprehensive with respect to the most basic stellar parameters often used for characterizing exoplanetary systems (see e.g. Figure 5; [67]). Given the statistical ubiquity of exoplanets, *in the near future nearly every star will be considered an exoplanet host star*, so proactively building and maintaining a database on nearby stellar targets would be a prudent step in support of the "New Worlds" mission envisaged by the 2010 Decadal Survey.

Science Gaps in this topic area:

- SCI-04 Planetary system architectures: occurrence rates for exoplanets of all sizes
- SCI-05 Occurrence rates and uncertainties for small planets (eta-Earth)
- SCI-07 Improve target lists and compilations of stellar parameters for exoplanet missions in operation or under study
- SCI-08 Mitigating stellar jitter as limitation to sensitivity of dynamical methods to detect exoplanets and measure their masses and orbits
- SCI-09 Dynamical confirmation of exoplanet candidates and determination of their masses and orbits
- SCI-10 Precursor surveys of direct imaging targets
- SCI-12 Measurements of accurate transiting planet radii

[7] NASA maintained such a stellar database (NASA Star and Exoplanet Database; NStED) during the SIM/TPF era, however support ceased in 2011.

Table 1 | Updated properties of the TRAPPIST-1 planetary system

Parameter	Value
Star	**TRAPPIST-1 = 2MASS J23062928−0502285**
Magnitudes[1]	$V=18.8$, $R=16.6$, $I=14.0$, $J=11.4$, $K=10.3$
Distance (pc)[1]	12.1 ± 0.4
Mass, M_* ($M_\odot$)[†]	0.0802 ± 0.0073
Radius, R_* ($R_\odot$)[†]	0.117 ± 0.0036
Density, ρ_* ($\rho_\odot$)	$50.7^{+1.2}_{-2.2}$
Luminosity, L_* ($L_\odot$)[†]	0.000524 ± 0.000034
Effective temperature, T_{eff} (K)[†]	$2{,}559\pm50$
Metallicity, [Fe/H][†] (dex)	$+0.04\pm0.08$

Planets	**b**	**c**	**d**	**e**	**f**	**g**	**h**
Number of unique transits observed	37	29	9	7	4	5	1
Period, P (days)	$1.51087081\pm0.60\times10^{-6}$	$2.4218233\pm0.17\times10^{-5}$	$4.049610\pm0.63\times10^{-4}$	$6.099615\pm0.11\times10^{-4}$	$9.206690\pm0.15\times10^{-4}$	$12.35294\pm0.12\times10^{-3}$	20^{+15}_{-6}
Mid-transit time, $T_0-2{,}450{,}000$ (BJD_{TDB})	$7{,}322.51736\pm0.00010$	$7{,}282.80728\pm0.00019$	$7{,}670.14165\pm0.00035$	$7{,}660.37859\pm0.00038$	$7{,}671.39767\pm0.00023$	$7{,}665.34937\pm0.00021$	$7{,}662.55463\pm0.00056$
Transit depth, $(R_p/R_*)^2$ (%)	0.7266 ± 0.0088	0.687 ± 0.010	0.367 ± 0.017	0.519 ± 0.026	0.673 ± 0.023	0.782 ± 0.027	0.352 ± 0.0326
Transit impact parameter, b (R_*)	$0.126^{+0.092}_{-0.078}$	$0.161^{+0.076}_{-0.084}$	0.17 ± 0.11	$0.12^{+0.11}_{-0.09}$	0.382 ± 0.035	0.421 ± 0.031	$0.45^{+0.22}_{-0.29}$
Transit duration, W (min)	36.40 ± 0.17	42.37 ± 0.22	49.13 ± 0.65	57.21 ± 0.71	62.60 ± 0.60	68.40 ± 0.66	$76.7^{+2.7}_{-2.0}$
Inclination, i (°)	$89.65^{+0.22}_{-0.27}$	89.67 ± 0.17	89.75 ± 0.16	$89.86^{+0.10}_{-0.12}$	89.680 ± 0.034	89.710 ± 0.025	$89.80^{+0.10}_{-0.05}$
Eccentricity, e (2σ upper limit from TTVs)	<0.081	<0.083	<0.070	<0.085	<0.063	<0.061	-
Semi-major axis, a (10^{-3} AU)	11.11 ± 0.34	15.21 ± 0.47	$21.44^{+0.66}_{-0.63}$	$28.17^{+0.83}_{-0.87}$	37.1 ± 1.1	45.1 ± 1.4	63^{+27}_{-13}
Scale parameter, a/R_*	$20.50^{+0.16}_{-0.31}$	$28.08^{+0.22}_{-0.42}$	$39.55^{+0.30}_{-0.59}$	$51.97^{+0.40}_{-0.77}$	$68.4^{+0.5}_{-1.0}$	$83.2^{+0.6}_{-1.2}$	117^{+50}_{-26}
Irradiation, S_p (S_{Earth})	4.25 ± 0.33	2.27 ± 0.18	1.143 ± 0.088	0.662 ± 0.051	0.382 ± 0.030	0.258 ± 0.020	$0.131^{+0.081}_{-0.067}$
Equilibrium temperature (K)[‡]	400.1 ± 7.7	341.9 ± 6.6	288.0 ± 5.6	251.3 ± 4.9	219.0 ± 4.2	198.6 ± 3.8	168^{+21}_{-28}
Radius, R_p (R_{Earth})	1.086 ± 0.035	1.056 ± 0.035	0.772 ± 0.030	0.918 ± 0.039	1.045 ± 0.038	1.127 ± 0.041	0.755 ± 0.034
Mass, M_p (M_{Earth}) (from TTVs)	0.85 ± 0.72	1.38 ± 0.61	0.41 ± 0.27	0.62 ± 0.58	0.68 ± 0.18	1.34 ± 0.88	-
Density, ρ_p (ρ_{Earth})	0.66 ± 0.56	1.17 ± 0.53	0.89 ± 0.60	0.80 ± 0.76	0.60 ± 0.17	0.94 ± 0.63	-

The table shows the values and 1σ errors for the parameters of TRAPPIST-1 and its seven planets, as deduced for most parameters from a global analysis of the Spitzer photometry, including *a priori* knowledge of the stellar properties. M_*, R_*, ρ_* and L_* are the stellar mass, radius, density and luminosity, respectively, given in units of the mass, radius, density or luminosity of the Sun ($M_\odot$, $R_\odot$, $\rho_\odot$, $L_\odot$). R_p, S_p, M_p and ρ_p are respectively the radius, irradiation, mass and density of the planet. BJD_{TBD}, barycentric Julian date in the barycentric dynamical time standard. Masses of the planets and upper limits on their eccentricities were deduced from the analysis of the TTVs (see text and Methods). We note that the planet TRAPPIST-1d does not correspond to the discarded 'TRAPPIST-1d' candidate presented in ref. 1 (see text).

†Informative prior probability distribution functions were assumed for these stellar parameters (see Methods).

‡Assuming a null Bond albedo.

Figure 5: Table of stellar and exoplanet properties for the TRAPPIST-1 system from [67]***, exemplifying the remarkable level of precision enabled for measured exoplanet properties when stellar parameters are measured quite accurately***

6. Exoplanet Atmospheres and Biosignatures

The first indications that atmospheres were present in solar system planets other than Earth were telescopic observations of variable cloud patterns on the disks of Mars and Jupiter. As in all areas of astronomy, the detection of spectral features (of a planetary atmosphere or surface) was needed to reveal their chemical composition. Remote spectroscopy first revealed the presence of gaseous CH_4 in the atmospheres of the outer planets and Titan, and gaseous CO_2 in the atmospheres of Venus and Mars. Remote spectroscopy of Earth, approximated by observations of lunar Earthshine, shows prominent H_2O and O_2/O_3 spectral features [142]. These groundbased telescopic observations of the solar system planets reveal the unique features of our habitable Earth and suggest what spectroscopic observations of exoplanet analogs could reveal.

The occurrence of atmospheres across the parameter space of planetary insolation and escape velocity has recently been defined by the "cosmic shoreline" of Zahnle and Catling [21]. This shows that exoplanets large enough for spectroscopic measurements in the next decades are likely to retain atmospheres, and thus atmospheres (and not surfaces) will be the primary focus of exoplanet characterization. To date spectroscopic characterization of atmospheres has been obtained through 1) direct imaging of thermal emission from exoplanets or their brown dwarf analogs; 2) transmission spectra of transiting exoplanets; 3) emission spectra of transiting exoplanets eclipsed by their parent star, and 4) emission spectra modulated by orbital phase. For all four methods, observational selection effects favor the detection of hotter, brighter planets. Imaging observations are limited by the contrast capabilities and inner working angles of existing instruments: currently these fall well-short of providing access to potentially habitable planets. Transit spectroscopy overcomes these limitations. The photon noise of the host star, the small fractional limb area of the planet's stratosphere that can be probed in transmission, and the short duration of transit events (which necessitate coaddition of data from numerous separate transits) limit the sensitivity of transit spectra.

A key question for exoplanet spectroscopy is the nature of sub-Neptune and super-Earth atmospheres. Kepler mission results show these planet types to be common [15] but there are no examples to study in our solar system. To date there have been no clear detections of exoplanets in reflected light, and no spectral measurements of exoplanets cooler than 500 K. Important goals for the future are to bring overlap in the mass/temperature regime of exoplanets probed by spectroscopy and the mass/temperature regime of the solar system planets, and especially to spectrally characterize rocky planets in stellar habitable zones in search of Earth-like environments and the possible presence of life.

"Recommendation: NASA should lead a large strategic direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars."

NAS Exoplanet Science Strategy (2018)

> *"Transit spectroscopy and direct detection measurements draw on increasingly sophisticated models of planetary atmospheres, which include detailed molecular chemistry, cloud formation, and circulation flows driven by stellar irradiation."*
>
> *New Worlds, New Horizons: A Mid-term Assessment (2016)*

The portfolio of NASA's Exoplanet Exploration Program (ExEP) currently includes relatively little work on exoplanet atmospheres and biosignatures. Observations are largely carried out with NASA Astrophysics assets managed outside the Program and by groundbased telescopes & instruments. Modeling is supported by multiple NASA ROSES Programs including the NASA Astrobiology Institute, with overall coordination by the NASA Nexus for Exoplanet System Science (NExSS). Nevertheless, studies of exoplanet atmospheres are directly relevant to the key Program goals of characterizing the properties of exoplanets and identifying candidates that could harbor life. A coronagraph will be flown on the WFIRST mission as a technology demonstrator and may spectrally characterize of a small sample of giant exoplanets. The long-term goal of the Program remains the flight of Astro2010's New Worlds Mission to directly image and spectrally characterize potentially habitable exoplanets. With increasing involvement in this research area as these future missions become better defined, ExEP thus monitors with interest current work in exoplanet atmospheres and biosignatures.

6.1. Atmospheres: State of the field

The first detection of an exoplanet atmosphere was an HST measurement of optical Na I absorption in a transiting hot Jupiter [143]. The lower than expected abundance suggested a cloudy atmosphere. An escaping upper atmosphere was detected in Ly α absorption in 2003 [144]. The Spitzer Space Telescope provided the first detection of eclipsed infrared continuum emission from hot Jupiters [145, 146], allowing direct measurement of an exoplanet's temperature for the first time. Since then the detection of spectral features has been claimed in nearby two dozen transiting planets. Of these only Na I, H_2O, and Ly α have been confirmed [147]. Planets smaller than Neptune are of particular interest for atmospheric characterization, but the extant transit spectra lack molecular absorptions and suggest a high cloud or haze layer [148]. Orbital phase curves for hot Jupiters have shown offsets between the longitude of peak thermal emission and the substellar longitude [149], suggesting the redistribution of heat between the day and night sides of a tidally-locked planet. Large surveys with HST and Spitzer are building complete spectra of transiting planets from the near-UV into the mid-infrared [150], and find a range of H_2O absorption band strengths which are interpreted as a range of clear to cloudy atmospheres.

Direct imaging of hot young planets has shown the presence of absorptions from methane, carbon monoxide, and water [151, 152]. Counter-intuitively, faint exoplanets can be more readily detected with high resolution spectroscopy than with broad-band images, by the method of cross-correlating a template molecular spectrum with hundreds or thousands of lines with the observed spectrum. While each line is detected with very poor S/N, the ensemble of lines provides the ability to detect the template species in the target. This has worked both for planets spatially resolved from their star in coronagraphic images [153] and in the combined light of the star and planet [154]. Recent examples of HST and ground exoplanet spectra are shown in Figure 6.

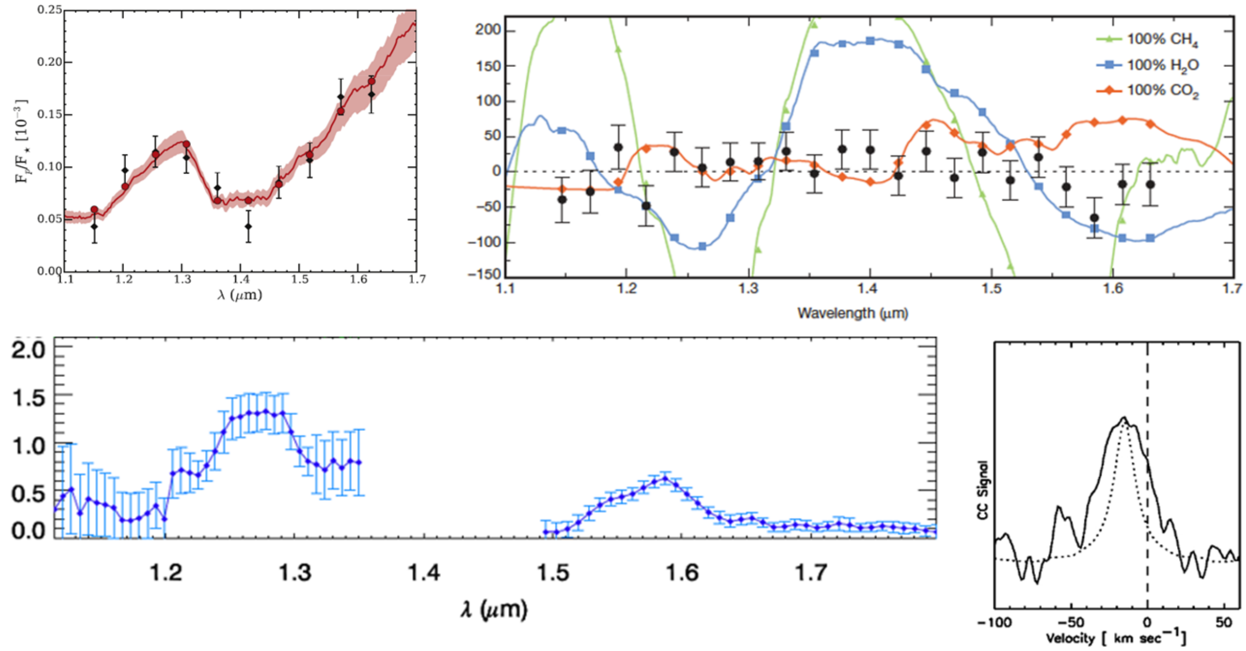

Figure 6: **Recent spectroscopy results for exoplanet atmospheres. Top left: HST/WFC3-IR transmission spectrum of the prototype transiting hot Jupiter HD 209458 showing the observations (black points) vs. models with H2O absorption (red points). H_2O absorption is robustly detected** *[155]***. Top right: Similar data (black points) for the transiting mini-Neptune GJ 1214b showing the lack of molecular absorption features** *[148]***. Bottom left: A coronagraphic spectrum of the young giant planet 51 Eridani b made with the Gemini planet imager. The presence of CH_4 and H_2O absorptions is indicated** *[152]***. Bottom right: Cross-correlation peak between a template CO and H_2O near-IR spectrum and the observed high resolution spectrum of the young exoplanet Beta Pictoris b. The peak intensity indicates the presence of these molecules in the planet's atmosphere, while its width in excess of the instrumental profile reflects the v*****sini* **of the planet's rotational velocity** *[153]***.**

"We have only the most rudimentary ideas about what conditions are necessary for and conducive to the formation of life. Even here, modern astronomy has a key role to play, by finding and characterizing planets with the features that allow for life around stars other than the Sun. It will require study of individual planets by directly sensing their light to find the molecular signposts of habitability in the atmospheres and surfaces of these distant bodies."

New Worlds, New Horizons in Astronomy & Astrophysics (2018)

6.2. Atmospheres: Current and upcoming activities

The James Webb Space Telescope (JWST) is a general-purpose observatory that will begin to make important contributions to exoplanet spectroscopy around 2021. Direct imaging at 3-5 microns will be very sensitive to cool (T< 400 K), self-luminous, giant exoplanets undetectable

"JWST, with its superb mid-infrared capability, will also use imaging and spectroscopy transit techniques to study the atmospheres of exoplanets, a science capability that has been amply demonstrated by the currently operating Spitzer Space Telescope. JWST will be a premier tool for studying planets orbiting stars that are smaller and cooler than the Sun."

New Worlds, New Horizons in Astronomy & Astrophysics (2010)

from the ground in the near-infrared. JWST coronagraphic surveys will reveal the population of such objects beyond 1.5 arcsecond separations around young (age < 1 Gyr) stars, potentially at contrasts as small as 10^{-6}, and tracing molecular bands of CH_4, CO, and H_2O [156]. JWST's transit spectroscopy capability will be even more important, enabling the first attempts at detection of biosignatures in potentially habitable exoplanets. Focusing on red dwarf stars identified by the K2 and TESS missions, around which rocky planets can be detected with transit depths of 0.1-1.0%, JWST should obtain spectra of numerous super-Earth and mini-Neptune atmospheres. Mid-IR wavelengths should penetrate cloud layers that have limited the detection of absorption features in near-IR transit spectra to date. These observations should be able to establish definitive trends in atmospheric composition and cloud properties as a function of planet or host star properties [157]. Detections of biosignatures (such as O_2/O_3 in disequilibrium with CH_4) will be difficult, only being possible for bright red dwarfs hosting large (but not too massive) exoplanets in the HZ, good achieved telescope stability, and with a major investment in observing time [158, 159]. Overall the JWST mission should provide spectra for dozens warm exoplanets with greater sensitivity than ever before.

An upgrade to the ESO Very Large Telescope (VLT) has recently been funded that will feed optical fibers from the focal plane of the SPHERE coronagraph to the ESPRESSO high resolution spectrograph. The ambitious goal of this experiment is to directly detect proxima Centauri b at visible wavelengths. If achieved this would remove the sini ambiguity in the planet mass, constrain the planet radius and albedo, and search for H_2O and O_2 through cross-correlation with template molecular spectra. Roughly 60 nights of observing, spread over 3 years at the epochs of optimal radial velocity offset from telluric spectral lines, would be required. Even if this goal is not achieved, the experiment will provide valuable experience for a more capable system that might eventually be deployed on a future giant segmented mirror telescope (GSMT) [160]. Improvements needed to enable high contrast coronagraphic imaging at visible wavelengths are beginning to be pursued [161].

The Wide Field Infrared Survey Telescope (WFIRST) will fly a CoronaGraph Instrument (CGI) as a technology demonstrator in the mid-2020s. Using deformable mirrors to correct optical wavefronts, CGI should be capable of detecting giant exoplanets in reflected light at contrasts as small as a few times 10^{-9} of the central star at separations as small as 0.13 arcseconds. Two epochs of imaging detections would be sufficient to remove the *sini* ambiguiuty in the masses of planets detected by RV. CGI is expected to include an Integral Field Spectrograph (IFS) that will measure spectra at visible wavelengths (0.60-0.98 microns) at resolving power R = 50. CGI is being designed to detect multiple CH_4 absorption features, which would enable characterization of the metallicity, clouds, and hazes in the atmospheres of giant exoplanets discovered in advance by radial velocity or by the ESA Gaia mission. At least a half dozen planets with masses between 0.1-10 $M_{Jupiter}$, and spanning a temperature range of ~100-500 K should be accessible [162].

"What are the origins and compositions of clouds and hazes in ice/gas giants and how do these vary with system parameters? How do photochemistry, transport chemistery, surface chemistry, and mantle outgassing affect the composition and chemical processes in terrestrial planet atmospheres? What processes/properties set the modes of atmospheric circulation and heat transport in exoplanets and how do these vary with system parameters? What are the key evolutionary pathways for rocky planets?"

ExoPAG SAG 15 report

Giant segmented mirror telescopes (GSMTs) such as the Giant Magellan Telescope (GMT), European Extremely Large Telescope (ELT), and the Thirty Meter Telescope (TMT) will offer new capabilities for studying exoplanet atmospheres starting in the mid-2020s. When equipped with extreme AO coronagraphs analogous to GPI and SPHERE, they will offer inner working angles several times smaller than these current instruments. This will enable studies of hot young protoplanets still embedded in protoplanetary disks of the nearest star-forming regions. Due to the difficulty of controlling their large segmented primary mirrors the GSMTs are only expected to provide a modest improvement in raw image contrast vs. current systems. Exoplanet detections in broadband imaging are expected to be limited to contrasts of 10^{-8} or brighter for typical nearby star targets [163]. This is sufficient to detect Earth-sized planets in the 0.1 AU habitable zones of nearby mid- to late- red dwarf stars. With a maximum elongation of 37 mas, proxima Centauri b will be a prime target detectable outside the ELT's 20 mas IWA in the near-infrared. However, the total number of nearby red dwarfs with habitable zones large enough to be resolved by GSMTs is small, perhaps only a handful. The use of high dispersion spectroscopy and spectral template correlations (CO, O_2) to detect the targets could ease the raw contrast requirement to 10^{-5}, provided that an IFS is provided with sufficient field of view to find the target [164]. None of the GSMTs have baselined an extreme AO system as a first-generation instrument, and thus these ambitious imaging observations may not be possible until the late 2020s. Taking advantage of the excellent Strehl ratios that an ordinary AO system provides at 10 microns, the ELT's METIS instrument may be able to detect rocky planets at 10^{-6} contrast in a few nearby systems such a α Cen [165, 166].

ESA has recently selected the ARIEL mission[8] for its M4 flight opportunity (potential launch in 2028). ARIEL will provide simultaneous near and mid-infrared transit spectroscopy of a much larger sample of hot giant planets than JWST is likely to study, and fulfills the mission recommendation of the ExoPAG SAG 10 report [167]. However, ARIEL's small aperture size of ~1 m is insufficient for spectral observations of small terrestrial planets.

When spectra of small, rocky exoplanets in circumstellar habitable zones become available, the key interpretative question will be how similar they are to the terrestrial planets of our own solar system. The strong O_2 feature at 760 nm is a key difference between the Earth's spectrum and that of Mars and Venus, and thus is particularly important to measure for HZ exoplanets [168]. Recent work has shown possible abiotic pathways to a large O_2 mixing ratio [169], particularly for the higher radiation environments of red dwarf stars. Just as O_2 by itself may be a false positive for life, the absence of O_2 could be a false negative: the young Earth hosted life in the form of blue-

[8] https://ariel-spacemission.eu/

green algae before the rise of oxygen. It is therefore crucial to constrain the chemical context for oxygen in an exoplanet atmosphere [170], and not consider oxygen on its own as a definitive biosignature. A broad range of atmospheric species that could trace the presence of life were considered by Seager, Bains, and Petkowski [171]; consideration of the best alternative biosignatures continues to be an active area of research [172, 173]. While future large telescopes on the ground and in space are likely to be limited to detections of major atmospheric constituents only, the capability to detect O_2 and H_2O levels of present-day Earth could be within reach by the 2030s [174] – provided that the needed investments take place.

6.3. Atmospheres: Knowledge needed to inform ExEP Objectives

Spectroscopic analysis of photons transmitted, emitted, or reflected by exoplanets is essential for understanding their physical conditions, chemical compositions, and potential to harbor life. Exoplanets large enough to be accessible to spectroscopic study are expected to retain atmospheres whose properties can be diagnosed from their spectra. The Exoplanet Exploration Program seeks spectroscopic measurements of exoplanet atmospheres across a wide range of planet sizes, orbital distances, stellar types, and stellar activity in order to understand planetary formation, planetary evolution, and the galactic context for the planets of our Solar System.

Interpretation of exoplanet spectra is founded on thermochemical, dynamical, and radiative transfer models of exoplanet atmospheres. The Exoplanet Exploration Program seeks progress in models of atmospheric spectra and the retrieval of atmospheric parameters from real and simulated datasets, toward the goals of measuring atmospheric temperature-pressure profiles, the mixing ratios of spectrally active molecules, the presence and properties of clouds and hazes, rates of atmospheric escape, and (where applicable) the separation of atmospheric signatures from surface characteristics. Progress in laboratory measurements of molecular constants is needed to enable some of these modeling goals.

Rocky planets in habitable zones are the focus for astronomical searches for habitable planets and life. It is straightforward to establish habitability by detecting atmospheric water vapor in the spectrum of such a planet. If a biosignature gas such as O_2 is present, supporting evidence is required to favor a biological origin over possible abiotic sources. The Exoplanet Exploration Program seeks research on the range of possible biosignatures accessible to remote observation; integrated models of planetary lithospheres, hydrospheres, and atmospheres to establish the geochemical context of candidate biomarker gases; and studies of the stability and evolution of biosignature gas abundances over geologic time for a variety of host star environments.

Science Gaps in this topic area:
SCI-01 Spectral characterization of atmospheres of small exoplanets
SCI-02 Modeling exoplanet atmospheres

"Finding: Inferring the presence of life on an exoplanet from remote sensing of a biosignature will require a comprehensive framework for assessing biosignatures. Such a framework would need to consider the context of the stellar and planetary environment, and include an understanding of false negatives, false positives, and their observational discriminants."

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SCI-03 Spectral signature retrieval
SCI-09 Dynamical confirmation of exoplanet candidates and determination of their masses and orbits
SCI-10 Precursor surveys of direct imaging targets

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8. Appendix A: Acronym List

AAS	American Astronomical Society
AAT	Anglo-Australian Telescope
AAVSO	American Assocation of Variable Star Observers
AFTA	Astrophysics-Focused Telescope Assets
AIP	Astrophysics Implementation Plan
APASS	AAVSO Photometric All-Sky Survey
APD	Astrophysics Division (NASA HQ)
APOGEE	Apache Point Observatory Galactic Evolution Experiment
APS	Astrophysics Subcommittee
CGI	CoronaGraph Instrument (on WFIRST)
CTL	Candidate Target List (subset of TIC for TESS primary mission survey)
EC	Executive Committee
ECMP	Export Compliance Management Plan
ESS	Exoplanet Science Strategy, 2018 National Academies Report
EUV	Extreme Ultraviolet ($100 < \lambda < 912$ Å)
ExEP	Exoplanet Exploration Program
Exo-C	Exo-Coronagraph (Probe Study)
Exo-S	Exo-Starshade (Probe Study)
ExoPAG	Exoplanet Program Analysis Group
ExoTAC	Exoplanet Technical Analysis Committee
FUV	Far Ultraviolet ($912 < \lambda < 1700$ Å)
GSFC	Goddard Space Flight Center
HERMES	High Efficiency and Resolution Multi-Element Spectrograph (for the AAT)
HQ	NASA Headquarters
HSOY	Hot Stuff for One Year (astrometric catalog based on Gaia DR1 and PPMXL)
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KIC	Kepler Input Catalog
LAMOST	Large Sky Area Multi-Object Fibre Spectroscopic Telescope
MWM	Milky Way Mapper (multi-object spectroscopic survey of SDSS-V)
NASA	National Aeronautics and Space Administration
NPD	NASA Policy Document
NPR	NASA Procedural Requirements
NRA	NASA Research Announcement

NRC	National Research Council
NSPIRES	NASA Solicitation and Proposal Integrated Review and Evaluation System
NUV	Near Ultraviolet (1700 < λ < 4000 Å)
NWNH	New Worlds, New Horizons, see reference [3] a.k.a the 2010 Decadal Survey of Astronomy and Astrophysics
NWNH:AMA	New Worlds New Horizons: A Mid-Term Assessment (2016)
PCS	Program Chief Scientist
PCT	Program Chief Technologist
PDR	Preliminary Design Review
PE	NASA Program Executive
PI	Principal Investigator
PM	Program Manager
PPBE	Program Planning and Budgeting Exercise
PPM	Positions and Proper Motions (astrometric star catalog)
RAVE	Radial Velocity Experiment
ROSES	Research Opportunities in Space and Earth Sciences
SAG	Science Analysis Group
SAT/TDEM	Strategic Astrophysics Technology/Technology Development for Exoplanet Mission
SDSS	Sloan Digital Sky Survey
SE	System Engineer
SGL	Science Gap List
SMD	Science Mission Directorate
SME	Subject Matter Expert
SIG	Science Interest Group
SPIE	Society of Photo-Optical Instrumentation Engineers
TAC	Technical Assessment Committee
TIC	TESS Input Catalog
TDEM	Technology Development for Exoplanet Mission
TGL	Technology Gap List
TRL	Technology Readiness Level
UCAC	USNO CCD Astrograph Catalog
USNO	US Naval Observatory
WFIRST	Wide-Field Infrared Survey Telescope
XUV	X-ray + Extreme Ultraviolet (1 < λ < 912 Å)