Exoplanet Science Strategy

DETAILS

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Exoplanet Science Strategy

Committee on Exoplanet Science Strategy

Space Studies Board

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

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Preface

The NASA Transition Authorization Act of 2017 directed the National Aeronautics and Space Administration (NASA) to engage the National Academies of Sciences, Engineering, and Medicine in the development of a science strategy for the study and exploration of extrasolar planets in preparation for, and as an input to, the upcoming decadal surveys in astronomy and astrophysics and in planetary science. The NASA Science Mission Directorate (SMD) then enlisted the Space Studies Board (SSB) and the Board on Physics and Astronomy (BPA) to establish the Committee on Exoplanet Science Strategy. This committee was charged with surveying the status of the field and outlining key scientific questions for future research, as well as identifying opportunities for coordination with international, commercial, and not-for-profit partners. The complete statement of task is reprinted in Appendix A.

To address its task, the committee convened three in-person meetings and numerous teleconferences during its work from December 2017 through August 2018. The meetings included extensive conversations with the exoplanet science community, including leadership from NASA and the National Science Foundation (NSF), and featured presentations from a broad range of stakeholders, including mission scientists, individual investigators, international representatives, and philanthropic organizations. In addition, the committee issued a broad call for white papers that was targeted at the astronomy community, but open to anyone who wished to provide input to the study process. The complete white paper call and a list of the submitted white papers are reprinted in Appendix B. The full text of the submitted white papers is also available on the committee's website. Throughout this process, the committee coordinated its work with the concurrent National Academies Committee on the State of the Science of Astrobiology.

The committee would like to thank the many generous individuals throughout the exoplanet science community and its supporting institutions who contributed to the study process through presentations, written input, and discussions. A special thanks goes to the staff from the National Academies: David Lang, Nathan Boll, Chris Jones, Art Charo, Dionna Wise, Jim Lancaster, Richard Rowberg, Colleen Hartman, and former SSB director Michael Moloney.

Dave Charbonneau and Scott Gaudi, *Co-Chairs*
Committee on Exoplanet Science Strategy

Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Marcia J. Rieke, NAS, University of Arizona. She was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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Summary

Is the Solar System a cosmic rarity or a galactic commonplace? How do Earth-like planets form, and what determines whether they are habitable? Is there life on other worlds? The answers to some of the greatest questions about humanity's place in the cosmos are at hand. But what path should be taken to answer these questions?

The past decade has delivered remarkable discoveries in the study of exoplanets. Scientists have learned that most, if not all, stars host planets, and that small planets are ubiquitous. They have directly imaged young gas-giant exoplanets. They have probed the atmospheres of more than a hundred worlds and detected molecules and clouds. They have measured the rate of occurrence of terrestrial planets at distances from their stars where surface oceans might be possible. They have even identified a handful of such worlds transiting nearby small stars, calling out with each passing orbit to investigate if they too host life. Hand-in-hand with these advances, a theoretical understanding of the myriad of processes that dictate the formation and evolution of planets has matured, spurred on by the avalanche of unexpected discoveries. Appreciation of the factors that make a planet hospitable to life has grown in sophistication, as has understanding of the context for biosignatures, the remotely detectable aspects of a planet's atmosphere or surface that reveal the presence of life.

There are two overarching goals in exoplanet science, as follows.

Goal 1 is 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. This leads to three scientific findings that will guide an implementation strategy:

> **Finding:** Current knowledge of the demographics and characteristics of planets and their systems is substantially incomplete. Advancing an understanding of the formation and evolution of planets requires two surveys: First, it requires a survey for planets where the census is most incomplete, which includes the parameter space occupied by most planets of the Solar System. Second, it requires the characterization of the atmospheres and bulk compositions of planets spanning a broad range of masses and orbits.
>
> **Finding:** An understanding of planet formation requires a census of protoplanetary disks, young planets, and mature planetary systems across a wide range of planet-star separations.
>
> **Finding:** Characterizing the masses, radii, and atmospheres of a large number of exoplanets with a range of physical and orbital parameters for a diverse set of parent stars will yield fundamentally new insights into the formation and evolution of planets and the physics and chemistry of planetary environments.

Goal 2 is 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. This goal, in turn, leads to two guiding scientific findings:

Finding: The concept of the habitable zone has provided a first-order technique for identifying exoplanets that may be able to harbor life. A multiparameter holistic approach to studying exoplanet habitability, using both theory and observation, is ultimately required for target selection for biosignature searches.

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.

The quest to characterize potentially habitable planets and search for atmospheric biosignatures presents two paths, both of which demand exploration. In the near term, temperate rocky planets orbiting the closest small stars (known as M dwarfs) can be studied with facilities under construction. Several such planets are known and more will be discovered by the recently launched Transiting Exoplanet Survey Satellite (TESS) mission. However, understanding the foreign environment surrounding an M dwarf requires a substantial extrapolation of scientists' knowledge of habitability informed by the Solar System. Ultimately, the exoplanet community needs to develop the means to study potentially habitable planets orbiting more Sun-like stars. Developing this capability will require bold investments and a longer time scale to bear fruit, but along the way it will foster the development of the scientific community and the technologic capacity to understand a myriad of worlds that currently elude us. The requirements to pursue an Earth-Sun analogue imply an imager in space:

Finding: A coronagraphic or starshade-based direct imaging mission is the only path currently identified to characterize Earth-size planets in the habitable zones of a large sample of nearby Sun-like stars in reflected light.

Finding: Recently acquired knowledge of the frequency of occurrence of small planets, and advances in the technologies needed to directly image them, have significantly reduced uncertainties associated with a large direct imaging mission.

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. (Chapter 4)

Ground-based astronomy will also play a pivotal role. The two U.S.-led giant segmented mirror telescopes (GSMTs), the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT), will unveil an incredible discovery space in the study of planet formation, mature gas giants, and even terrestrial worlds:

Finding: The GMT and TMT will enable profound advances in imaging and spectroscopy of entire planetary systems, over a wide range of masses, semimajor axes, and wavelengths, potentially including temperate Earth-size planets orbiting M-type stars.

Finding: The technology roadmap to enable the full science potential of GMT and TMT in exoplanet studies is in need of investments, leveraging the existing network of U.S. centers and laboratories and current 8-10 meter class facilities.

Finding: GMT and TMT, equipped with high-resolution optical and infrared spectrographs, will be powerful tools for studying the atmospheres of transiting and nontransiting close-in planets, and have the potential to detect molecular oxygen in temperate terrestrial planets transiting the closest and smallest stars.

Finding: The detection of young planets in disks will provide the ground truth for the time scale of planet formation and permit studies of the dynamical interaction between disks and planets. With the high spatial resolution of the GMT and TMT, researchers will be able to search the inner parts of planet-forming systems.

Recommendation: The National Science Foundation (NSF) should invest in both the GMT and TMT and their exoplanet instrumentation to provide all-sky access to the U.S. community. (Chapter 4)

As found above, an essential input to inform an understanding of planet formation is a statistical census of the population of planets. While radial velocity surveys and transits, notably the revolutionary Kepler mission, have characterized the remarkable population of planets relatively close to their stars, knowledge of planets in the outer reaches of planetary systems is woefully incomplete. The 2010 Decadal Survey realized this, and hence it strongly recommended the Wide-Field Infrared Survey Telescope (WFIRST) mission.

Finding: A microlensing survey would complement the statistical surveys of exoplanets begun by transits and radial velocities by searching for planets with separations of greater than one AU (including free-floating planets) and planets with masses greater than that of Earth. A wide-field, near-infrared (NIR), space-based mission is needed to provide a similar sample size of planets as found by Kepler.

Finding: A number of activities, including precursor and concurrent observations using ground- and space-based facilities, would optimize the scientific yield of the WFIRST microlensing survey.

Through its coronagraphic instrument, WFIRST will also play an extremely valuable role in enabling a large direct imaging mission, both through retiring technical risk and by providing more sensitive constraints than are currently available for a potentially troublesome impediment for imaging missions—namely, exozodiacal dust.

Finding: Flying a capable coronagraph on WFIRST will provide significant risk reduction and technological advancement for future coronagraph missions. The greatest value compared to ground testing will come from observations and analysis of actual exoplanets, and in a flexible architecture that will allow testing of newly developed algorithms and methods.

Finding: The WFIRST-Coronagraph Instrument (CGI) at current capabilities will carry out important measurements of extrasolar zodiacal dust around nearby stars at greater sensitivity than any other current or near-term facility.

Recommendation: NASA should launch WFIRST to conduct its microlensing survey of distant planets and to demonstrate the technique of coronagraphic spectroscopy on exoplanet targets. (Chapter 4)

Mass is the most fundamental property of a planet, and knowledge of a planet's mass (along with a knowledge of its radius) is essential to understand its bulk composition and to interpret spectroscopic features in its atmosphere. If scientists seek to study Earth-like planets orbiting Sun-like stars, they need to push mass measurements to the sensitivity required for such worlds.

> **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.** (Chapter 4)

For the first time, the James Webb Space Telescope (JWST) will bring exoplanet atmospheric characterization efforts from a regime of limited observations to one of high-fidelity spectroscopic investigations of a comparative sample. The entire exoplanet research community would benefit from a strategic and systematic survey of exoplanet atmospheres with JWST, which has the potential to guide future observing strategies for years, if not decades.

> **Finding:** The combination of transiting planet detection with TESS, mass measurements with radial velocities, and atmospheric characterization with JWST will be transformative for understanding the nature and origins of close-in planets. Future space missions with broader wavelength coverage, a larger collecting area, or reduced instrumental noise compared to JWST would have greater reach to potentially habitable planets.
>
> **Recommendation: NASA should create a mechanism for community-driven legacy surveys of exoplanet atmospheres early in the JWST mission.** (Chapter 4)

The identification of life on an exoplanet will not be accomplished by a single team of researchers, nor by a single method. It will happen only when researchers bring together the combined insights of astrophysicists, planetary scientists, Earth scientists, and heliophysicists, and provide them the opportunity and resources to collaborate.

> **Finding:** The search for life outside the Solar System is a fundamentally interdisciplinary endeavor. The Nexus for Exoplanet Systems Science (NExSS) research coordination network encourages the cross-disciplinary and cross-divisional collaborations needed to support NASA exoplanet research and missions.
>
> **Recommendation: Building on the NExSS model, NASA should support a cross-divisional exoplanet research coordination network that includes additional membership opportunities via dedicated proposal calls for interdisciplinary research.** (Chapter 4)

Present and future NASA missions promise a wealth of measurements that contain the answers to the two overarching goals of understanding planets and searching for life. But the scientific implications of these data will not be fully realized without a thriving and engaged community in related fields of theoretical, laboratory, and observational science.

> **Finding:** Theoretical models are essential to plan and interpret observations of exoplanets, and are enabled by robust support via individual investigator grants.
>
> **Finding:** The limited lab and ab initio data covering the parameter space relevant to exoplanets is a barrier to accurate models of exoplanet atmospheres and interiors. Mechanisms to increase collaboration between exoplanet astronomers and experimental physicists and chemists would help overcome this barrier.
>
> **Finding:** Understanding of exoplanets is limited by measurements of the properties of the parent stars, including stellar mass, radius, distance, binarity, rotation period, age, composition, emergent spectrum, and variability.
>
> **Recommendation: NASA should support a robust individual investigator program that includes grants for theoretical, laboratory, and ground-based telescopic investigations; otherwise, the full scientific yield of exoplanet missions will not be realized.** (Chapter 4)

The search for life on other worlds is both a profound and a profoundly difficult endeavor, and the likelihood of success is maximized by marshaling, developing, and supporting all available talent. As a growing field, exoplanetary astronomy is particularly dependent on the effective development and retention of junior scientists because it is now putting into place the cohort of scientists who will be the senior leadership for many decades. Discrimination and harassment, as known to exist in the greater scientific workforce, likely affect the exoplanet community and serve as barriers to the participation of people from certain demographic groups. The Exoplanet Science Strategy therefore includes a strategy for developing and maintaining its human capital, including addressing its demographics and standards of professional conduct.

> **Finding:** To maximize scientific potential and opportunities for excellence, institutions and organizations can enable full participation by a diverse workforce by taking concrete steps to eliminate discrimination and harassment and to proactively recruit and retain scientists from underrepresented groups.
>
> **Finding:** Development and dissemination of concrete recommendations to improve equity and inclusion and combat discrimination and harassment would be valuable for building the creative, interdisciplinary teams needed to maximize progress in exoplanet science over the coming decades.

The great potential of exoplanet science demands large commitments. The work cannot be done by a single institution, but rather will engage federal partners and not-for-profit partners, and a consideration of international collaborations.

> **Finding:** By continuing to find novel ways of partnering with each other, and by removing or reducing institutional barriers to such partnerships, agencies may be able to better address some of the most profound scientific questions outlined in this study, which often require instruments, telescopes, or missions that are too ambitious or expensive for any individual agency to fund, build, and operate alone.

For generations, humans have looked up at the stars and wondered whether we are alone. Wonder at this very question unites us. This Exoplanet Science Strategy describes how researchers can aim to address this question in a generation. It is unknown whether this generation will be the first to learn that life is common throughout the galaxy, or the first to discern hints of a cosmic lonesomeness. What we do know is that we can be the first with the technological and scientific ability to answer the question, if we so choose.

1

Scientific Goals

The study of extrasolar planets and planet formation in general has exploded within the astrophysics community. In a 2016 survey of U.S. members of the American Astronomical Society (AAS), 21 percent of respondents listed exoplanets as their primary field of interest, 23 percent listed solar systems and planetary science, and 9 percent listed astrobiology.[1] This excitement reflects a field in which important discoveries are happening at a rapid rate, with the prospect of discoveries on the horizon that could fundamentally alter the view of humanity's place in the universe (Figure 1.1). With appropriate investment, researchers are on the cusp of learning fundamental truths about the galactic distribution of planets and planetary systems in which Earth and the Solar System reside. Are systems like the Solar System rare? Are planets like Earth rare? Does life exist on planets other than Earth and on planets orbiting other stars?

These questions have captured the imagination of the general public. Moreover, they have attracted a young and diverse cohort of scientists to this new field. With the accretion of a new community in progress and with opportunities for paradigm-shifting discoveries on the horizon, organized input from the exoplanet community to the decadal survey process is essential. The U.S. Congress and NASA have commissioned this report to provide such a perspective for the reference of the upcoming decadal survey committee. The aim of this report is to highlight strategic priorities for large, coordinated efforts that will support the scientific goals of the broad exoplanet science community. Along the way, this report will capture a subset of the vibrant, creative work currently under way in this diverse field.

Exoplanet science over the coming decades aims to achieve two overarching goals:

1. 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.
2. 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, researchers 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 2010 astronomy and astrophysics decadal survey, *New Worlds, New Horizons*, states that

> The search for life around other stars is a multi-stage process. … 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. Stars will then be targeted that are sufficiently close to Earth that the light of the companion planets can be separated from the glare of the parent star and studied in great detail; this will allow us to find signatures of molecules that indicate a potentially habitable environment.

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[1] See https://aas.org/files/aas_members_workforce_survey.pdf.

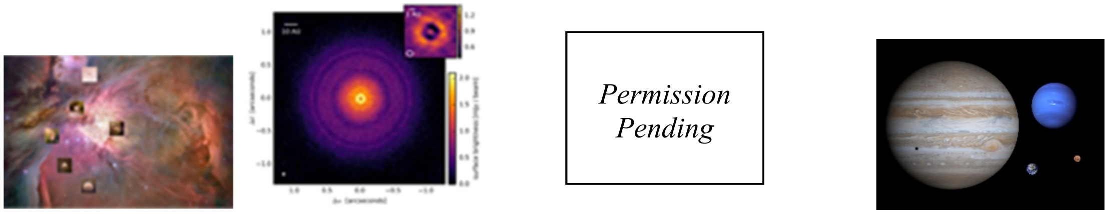

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FIGURE 1.1 From left: (1) The Orion star-forming region; (2) the protoplanetary disk around TW Hydra; (3) the directly imaged planetary system HR 8799; and (4) a diverse collection of Solar System planets. SOURCES: From left: (1) NASA, ESA, M. Robberto, HST Orion Treasury Project, L. Ricci; (2) Andrews et al. (2016); (3) Marois et al. (2010); (4) NASA.

In the intervening decade since the publication of that report, thousands of planets and high-quality planet candidates have been found orbiting stars other than the Sun. As summarized in Chapter 2, these discoveries show that

- Exoplanets are ubiquitous.
- Extrasolar planetary systems are diverse.
- Small planets with compositions that may resemble Earth and stellar irradiation consistent with the presence of surface liquid water are common.

Targets for planet characterization are abundant. The time has come for the next steps.

Given these discoveries, strategic investments over the coming decade would likely enable major progress toward the above goals. 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?

In this report, the committee describes a strategic plan to answer these questions through a combination of large, ambitious community-supported efforts and support for diverse, creative, community-driven investigator research. Projects capable of characterizing a full range of planets, including rocky bodies with sizes comparable to Earth, as well as the systems in which they reside, are needed. This strategy will allow the United States to take the next steps in the quest to understand the galactic diversity of worlds—their origins, histories, and atmospheric properties.

This report is organized as follows: Chapter 2 provides an overview of the current status of exoplanet science. Chapter 3 presents the scientific strategic plan to advance the two overarching goals over the next decade. Chapter 4 provides details about the technical and organizational requirements for the future investments highlighted in Chapter 3. Chapter 5 highlights the need for coordination among various organizations to achieve the strategic plan outlined here. Chapter 6 provides a timeline for the implementation of the strategic plan, broken down into near-, medium-, and long-term activities. Appendix A provides the committee's statement of task, Appendix B presents the call for white papers issued by the committee and lists all white papers submitted to the committee, Appendix C describes the exoplanet detection techniques in more detail, Appendix D provides a biosignature table, Appendix E presents short biographical sketches of the committee members and National Academies staff, Appendix F summarizes the acronyms used in this report and defines some quantities that might be unfamiliar to the reader, and Appendix G provides a glossary of selected terminology.

2

The State of the Field of Exoplanets

Although it was not the first detected exoplanet (see Box 2.1), the discovery of a planetary companion to the near solar analogue 51 Pegasi by Mayor and Queloz in 1995 launched the field of exoplanets. The discovery of 51 Peg b, which has a minimum mass of roughly 0.5 times the mass of Jupiter (M_J) but an orbital period of only about 4 days, surprised many. This is because the then-popular planet formation model predicted that such planets could not form in situ (e.g., Lin et al., 1996). Indeed, this is still the prevailing wisdom, and thus the discovery of 51 Peg b led to the realization that at least some fraction of exoplanets undergo large-scale migration from their birthplaces. The discovery of 51 Peg b heralded a general principle that has since held in the exoplanet field—namely, that planetary systems are remarkably diverse, and to "expect the unexpected."

Since the discovery of 51 Peg b, many thousands of exoplanets have been discovered via many different techniques (see Figure 2.1). A few notable milestones include the discovery of the first transiting planet, HD 209456b (Charbonneau et al., 2000; Henry et al., 2000); the discovery of the first exoplanet via transits, OGLE-TR-56b (whose photometric signal was first identified by Udalski et al., 2002, and whose planetary nature was confirmed via radial velocities by Konacki et al., 2003); the discovery of the first exoplanet via microlensing, OGLE 2003-BLG-235/MOA 2003-BLG-53Lb (Bond et al., 2003); and the discovery of the first directly imaged planetary system around HR 8799 (Marois et al., 2008). The field took another great leap forward with the launch of the NASA mission Kepler (Borucki et al., 2010), which brought the study of exoplanets into the statistical age.

METHODS OF DETECTING AND CHARACTERIZING EXOPLANETS: APPLICATIONS, BIASES, AND LIMITATIONS

By essentially every physical measure, planets are exceptionally diminutive, in particular in comparison to their host stars. This is the primary reason that it was not until nearly the end of the 20th century that the first definitive detections of exoplanets were made. It is useful to recall the relevant orders of magnitude that are involved. Considering Jupiter analogues to Sun-like stars, the size ratio is roughly 1 to 10, the mass ratio is roughly 1 to 1000, and the visible-light flux ratio is roughly 3 parts in a billion. For Earth analogues to Sun-like stars, the size ratio is roughly 1 to 100, the mass ratio is roughly 1 to 300,000, and the visible-light flux ratio is roughly 1 part in 2 billion.

Since nearly all detection methods rely on either the indirect influence of the exoplanet on its parent star or the direct detection of the planet in the vicinity of its parent star, these ratios make the detection of planets even as large as Jupiter incredibly difficult.

In this section the committee briefly reviews the primary methods that have been used to detect and characterize exoplanets. The goals of this section are to outline the regions of exoplanet and host star parameter space in which these methods are most sensitive, and to highlight the intrinsic biases and limitations of each method, which ultimately lead to the requirement that the full arsenal of methods needs to be used to obtain as complete a picture of the demographics and characteristics of planets as possible. In Appendix C, the committee describes these methods in somewhat more physical and mathematical detail for the interested reader.

BOX 2.1
The Early Days of Exoplanet Discovery

Although the concept that other stars might host planetary systems like Earth's is ancient, up to roughly 30 years ago, scientists did not know whether other stars hosted planetary systems.

Perhaps the first suggested detection of a planetary companion that ultimately turned out to be confirmed was the claim by Campbell et al. (1988) of a planetary companion to gamma Cephei Ab using the radial velocity technique. While they were hesitant to definitively ascribe their observed Doppler signal with a period of roughly 3 years and an amplitude of roughly 25 m/s to a 2 M_J companion with orbital separation of a few AU, subsequent observations by Hatzes et al. (2003) confirmed that the signal was, indeed, due to a planetary companion to gamma Cep Ab.

Latham et al. (1989) announced a companion to the Sun-like (F9V) star HD 114762 with minimum mass of 11 M_J and a period of roughly 84 days—that is, similar to the orbital period of Mercury. In the title of the article, the companion was referred to a "probable brown dwarf," although they also speculated that it might be a giant planet. Part of the skepticism of the planetary nature of the companion was due to the fact that its minimum mass was sufficiently high that it had a nonnegligible (although very small) chance of being a nearly pole-on binary, part was due to the high eccentricity and close period, and part was due to the fact that the definition of a planet at the time anything with a mass of less than 10 M_J. Subsequently, analogues of HD114762b have been found.

The first planetary system was not discovered around a main sequence or even an evolved star, but rather a stellar remnant. In 1992, Wolszczan and Frail (1992) announced their discovery of two planets with masses of roughly four times the mass of the Earth with periods of roughly 67 and 98 days orbiting the pulsar PSR 1257+12. Later, a third planet with a mass of only slightly larger than the mass of the Moon would be discovered; to date this is the lowest mass exoplanet yet discovered. Planetary companions to pulsars have since been shown to be quite rare, with only one additional confirmed planetary companion to a pulsar (Sigurdsson et al., 2003).

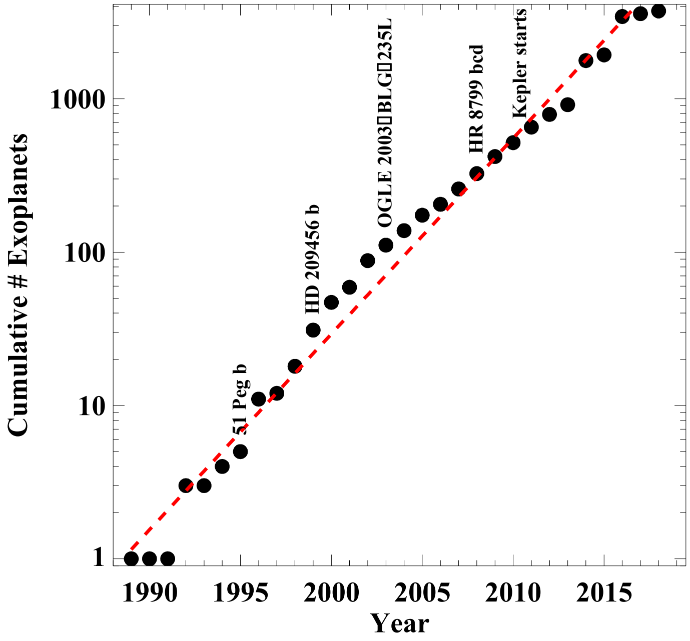

FIGURE 2.1 The cumulative number of exoplanets discovered versus the year of discovery up to July 2016. Several milestone discoveries are noted. To date, thousands of exoplanets have been discovered using 10 different techniques and the number of known planets roughly doubles every 28 months. SOURCE: A. Weinberger using confirmed planets from the NASA Exoplanet Archive.

Radial Velocity

The radial velocity (RV), or Doppler technique, is an indirect method that relies on measuring the Doppler shift of the star as it orbits the center-of-mass of the planet/star system. The amplitude of the Doppler shift is of order 10 m/s and the period is approximately 12 years for a Jupiter analogue orbiting a Sun-like star. For an Earth analogue the amplitude is roughly 10 cm/s and the period is roughly 1 year. For a "hot Jupiter" orbiting a Sun-like star with a period of 3 days, the amplitude is typically 150 m/s. Current state-of-the-art instruments, telescopes, and data reduction methods yield Doppler precisions of roughly 1 m/s on mature, Sun-like stars. However, Earth imparts a signal of only 9 cm/s on the Sun, and thus additional instrumentation, observations, and analysis methods are needed to detect Earth analogues.

The relatively weak function of the velocity amplitude on the planet period makes the RV method able to detect planets over a broad range of parameter space. The reflex velocity of a star depends linearly on the planet mass, and decreases with increasing stellar mass and orbital period. Because of the weak dependence on orbital period, the RV technique is able to detect planets in orbits from a few days to several years, with the upper limit on the detectable period set not only by the radial velocity precision but also by the time baseline. For example, a Neptune-mass planet in a circular orbit that is viewed edge-on will induce a stellar velocity of 1.5 m/s in a 1-year orbit, and 0.95 m/s in a 4-year orbit. However, it is important to note that RV observations provide little detailed information about the detected planet itself, as RV observations alone provide only the lower limit on the mass of the planet, and a subset of the full Keplerian orbital parameters (period, eccentricity, and argument of periastron).

Finally, high-resolution spectroscopy is increasingly being used as a method for measuring exoplanet atmospheres with transmission spectroscopy and high-contrast imaging techniques. This work requires the same very stable spectrographs that precision RVs require.

Transits

Planets in nearly edge-on orbits can be detected via transits when the planet passes in front of the face of the star, resulting in a relatively brief, periodic, shallow dip in the brightness of the star. For a hot Jupiter orbiting a solar-type star, the probability that the planet will transit is 10 percent, the depth of the transit is 1 percent, and the transit lasts for a few hours. For an Earth analogue, the transit probability is roughly 0.5 percent, the depth is roughly 0.01 percent, and the duration is 10 hours, corresponding to a duty cycle of only 0.15 percent. Transits of Jupiter-size planets on relatively short orbits (roughly less than 10 days) around Sun-like stars can be detected from the ground, whereas detecting transits of Earth analogues requires a dedicated space mission, which was the primary motivation of NASA's Kepler space telescope. Roughly Earth-size planets on shorter period orbits transiting smaller stars, such as potentially habitable planets orbiting low-mass stars (or M dwarfs), can and have been detected from the ground.

The detection of transits of a planet alone yields the period of the orbit, and the radius of the planet (given a measurement of the radius of the star), and the density of the star (Seager and Mallen-Ornelas, 2003). However, when combined with the RV detection of the planet, it is also possible to determine the planetary mass and density, which is the first step in determining its basic nature.

It is also possible to detect the existence of additional, nontransiting planets in transiting systems by searching for transit timing variations (TTVs). The detection of TTVs in multiple planet systems also enables the measurement of the masses of the planets without measuring the reflex RV they induce on their parent star. However, it is important to note that the detectability of TTV signals depends on the mass of the planetary perturber, and the proximity of the perturber to mean motion resonances. Therefore, TTVs are not a uniform or unbiased method of measuring exoplanet masses.

Transiting planets also present the opportunity to study the planetary atmosphere without the need to spatially resolve the planet from the star: atoms, molecules, and aerosols induce wavelength-dependent absorption of starlight as it passes through the planetary atmosphere during transit. Observing these effects (by comparing stellar spectra in and out of transit) allows astronomers to deduce the atmospheric composition; this method is called "transmission spectroscopy." Similarly, observations gathered during secondary eclipse (when the planet is out of view) can be subtracted from observations when both the star and planet are in view, to deduce the hemisphere-integrated planetary emission spectrum; this technique is termed "emission spectroscopy," or "secondary-eclipse spectroscopy."

Direct Imaging

Detecting exoplanets via direct imaging requires resolving the light of an orbiting exoplanet from its parent star. The challenges of direct imaging are generally the large flux ratio between the planet and the star, and the small angular separation between the planet and the much brighter host star. Thus, planets with larger flux ratios and larger angular separations are the easiest to detect.

In all cases where planets have been directly imaged to date, the detections are of young (<300 million years), giant (>2 M_J), self-luminous planets whose luminosity and temperature are powered by released gravitational potential energy from formation, resulting in near-infrared planet-to-star flux ratios as large as one part in 10^6 to 10^4. Flux ratios of this order can be detected via combinations of large ground-based telescopes, advanced adaptive optics, coronagraphy, and sophisticated image processing. However, since young stars are almost inevitably moderately distant from Earth, with distances to the closest young star associations typically 150 pc (500 light-years), the necessary sensitivity is only possible for angular separations beyond a few tenths of an arcsecond from the parent star. Hence almost all the imaged planets are giant planets orbiting at separations of 20 times the distance from Earth to the Sun (also referred to as an astronomical unit, or AU), or further. As these planets are directly detected, it is also possible to obtain their spectra, which allows for inferences about their atmospheric composition.

The flux ratios of mature planets that are in thermal equilibrium with their host stars are typically much smaller. An Earth analogue orbiting a Sun-like star at a distance from Earth of 10 parsecs has a flux ratio in reflected light of order 10^{-10}, and the maximum angular separation is roughly 0.1 arcseconds. For a Jupiter analogue in the same system, the flux ratio is several times larger, although the separation is five times larger. Directly detecting such systems requires sophisticated techniques to suppress the light from the star. Two promising techniques, which are described in detail later, are internal coronagraphs and external occulters (starshades).

Detecting mature planets in thermal emission is easier in terms of flux ratio than detecting them in reflected light, as the flux ratios are generally more favorable by roughly 4 orders of magnitude. However, the technical challenges of imaging planets in thermal emission are greater. This is because the typically small separation of planets from their host stars, combined with the large diffraction limit of monolithic telescopes of reasonable size at thermal infrared wavelengths, prevent resolving most planets at these wavelengths with traditional telescopes. As a result, detecting and characterizing planets in the thermal infrared, except for those possibly around the Sun's nearest neighbors, requires long baseline interferometry, which has even greater technical challenges. Thus, detecting mature planets in reflected light is currently believed to be the more straightforward path.

Direct detection allows a measurement of the planet's spectrum, or flux as a function of wavelength. Spectra are powerful probes of a planet atmosphere's composition (molecules) and structure (temperature-pressure profile). Transit spectroscopy (see the section "Transits," earlier in this chapter, and Figure 2.8, later) samples a small fraction of the planet's atmosphere at relatively low pressures, and is strongly subject to the veiling effect of hazes and clouds. Direct resolved spectroscopy, on the other hand, probes either reflected light or thermal emission coming nearly directly from the entire hemisphere of the planet, and thus probes much deeper into the atmosphere of the planet down to much higher pressures, and is relatively immune to clouds and hazes (Morley et al., 2015), and potentially able to study the planetary surface. High-resolution spectroscopy can also provide direct measurements of a planet's spin, and enable Doppler mapping.

The ultimate goal of facilities that are designed to measure the reflected or thermal emission of Earth analogues is to search for signatures of habitability, and perhaps even find biosignatures, aspects of a planet's atmosphere or surface that provide evidence of inhabitance. This is discussed in more detail later in this chapter, in the section "The Search for Life on Exoplanets."

Microlensing

Microlensing is an indirect method of detecting exoplanets that is primarily useful for the statistical determination of the demographics of exoplanets over a broad range of host star and exoplanet parameter space. Microlensing surveys are primarily useful for the statistical determination of exoplanet demographics because the planetary systems detected by microlensing are typically at distances of many kiloparsecs, and thus it is generally not possible to characterize individual planets detected by microlensing surveys.

Microlensing uses the gravitational bending of light from a background star by a foreground planet and its host to magnify the background star. This magnification, which can last from a few days to hundreds of days, is called a "microlensing event." Planetary companions to the foreground host are detected through perturbations of this microlensing event. It is important to note, however, that an isolated planet can also magnify a background star, and thus microlensing is sensitive to free-floating planets.

Microlensing is most sensitive to planets with separations of a few AU, although with a space-based mission, the sensitivity can span a much broader range of separations. In principle, microlensing is sensitive to planets with masses as low as a few lunar masses.

Because of the low probability of detecting a stellar-mass microlensing event, and the lower probability of detecting the planetary perturbation even in the case that the microlensing event is detected and assuming the planetary companion exists, microlensing surveys for exoplanets generally require continuously monitoring hundreds of millions of stars on daily time scales to detect the microlensing events, and then monitoring the known microlensing events on hourly to daily time scales to detect the planetary perturbations.

Planets detected via microlensing measure the mass-ratio between the planet and the star, and the instantaneous projected separation between the planet and host star in units of the Einstein ring radius. Fortunately, as described in detail in Chapter 4, in the section "Expanding the Statistical Census of Exoplanets," a space-based microlensing survey, such as that which will be carried out by WFIRST, will enable the routine measurement of the mass of both the host star and the planet. This is because the approximately 10-fold increase in angular resolution of WFIRST compared to typical ground-based seeing will enable the measurement of several higher-order effects that will break the usual microlensing degeneracy, in which one measures only a degenerate combination of the mass and distance to the host star, and relative proper motion of the host lens and source.

Astrometry

Astrometry detects planets by measuring the reflex motion of the star in the plane of the sky. For an Earth analogue at distance of 10 pc, the astrometric signal is roughly 0.3 microarcsecond, which is well below any realistic astrometric accuracy achievable from the ground. Furthermore, the sensitivity of astrometry to planets with periods longer than the duration of the astrometric survey drops precipitously (e.g., Casertano et al., 2008).

The European Space Agency (ESA) Gaia satellite is the first space-based astrometric mission with the sensitivity to detect exoplanets. While Gaia will have the most exquisite astrometric accuracy to date (<10 microarcseconds for stars with $V < 12$), it will nevertheless generally be sensitive to planets with masses only several times the mass of Jupiter at separations of less than roughly 3 AU for a Sun-like host.

WHAT HAS BEEN LEARNED ABOUT EXOPLANETS IN THE PAST 30 YEARS?

The next few sections describe what has been learned about exoplanets, both their demographics and their properties, using the various detection and characterization techniques briefly mentioned above. The most important of these are as follows:

- Planetary systems are ubiquitous and surprisingly diverse, and many bear no resemblance to the Solar System.
- A significant fraction of planets appear to have undergone large-scale migration from their birthsites.
- Most stars have planets, and small planets are abundant.
- Large numbers of rocky planets been identified and a few habitable zone examples orbiting nearby small stars have been found.
- Massive young Jovians at large separations have been imaged.
- Molecules and clouds in the atmospheres of large exoplanets have been detected.
- The identification of potential false positives and negatives for atmospheric biosignatures has improved the biosignature observing strategy and interpretation framework.

The Demographics of Exoplanets

The first step to understanding the complex processes involved in planet formation is the determination of a statistical census of the demographics of exoplanets over as broad a range of planet and host-star properties as possible. Understanding how planets form is not only interesting in its own right, it informs understanding of the prevalence of potentially habitable worlds—for example, by providing clues to the dominant processes of water delivery to rocky planets in the habitable zones of their parent stars. Formation models that aim to understand the demographics of mature planetary systems need to ultimately start from realistic physical conditions, and therefore be informed by observations of protoplanetary and debris disks.

Radial Velocities

Precise RV measurements benefit from the longest time baselines of exoplanet discovery methods (Mayor and Queloz 1995). Continued improvement in Doppler precision as well as long-term stability have permitted the coherent linking of data sets across various instrumental platforms and over time. Dedicated ground-based efforts from spectrographs operating on both small telescopes and large telescopes have revealed a rich diversity of exoplanets through their mass and orbital properties (Marcy and Butler 2000). Despite being an indirect method that targets only one star at a time, increasing Doppler sensitivity from 100 m/s to 1 m/s has enabled the RV technique to quantify the statistical occurrence of planets at small to moderate orbital radii and to correlate the results as a function of host star properties.

The primary results from the myriad of radial velocity surveys are as follows:

- There exists a (largely unforeseen) population of short-period “hot Jupiters” and paucity of brown dwarfs located close to their parent stars (e.g., Wright et al., 2012).
- Gas giant planets have been detected with semimajor axes comparable to Jupiter and beyond. For example, HD 75784 b orbits at $a = 6.6$ AU (Giguere et al., 2015).
- Short-period giant planets are more commonly found orbiting stars with high metallicity (Gonzalez 1997; Santos et al., 2004; Fischer and Valenti, 2005).

- The occurrence of giant planets tends to increase with orbital period; modulo a "pile-up" of "hot Jupiters" around 3-day orbital periods (Cumming et al., 2008). This pile-up appears to occur only for metal-rich stars, which also preferentially host high-eccentricity giants interior to 1 AU, likely implying that giant planets in close orbits have been emplaced via planet-planet interactions in systems capable of forming multiple giants (Dawson and Murray-Clay, 2013).
- Low-mass planets at short orbital periods of less than 50 days are more common than giant planets (Howard et al., 2010; Mayor et al., 2011). These results foreshadowed the Kepler result, which extended down to smaller (less massive) planets.
- Relatively short-period giant planets are less common around M dwarfs (see Figure 2.2; Johnson et al., 2010, and also Figure 4 of Wang and Fischer, 2015).
- Earth-mass planets in the habitable zones of the nearest M dwarfs have been discovered (e.g., Anglada-Escude et al., 2016; Bonfils et al., 2018). These planets are ripe targets for atmospheric characterization with future instruments.

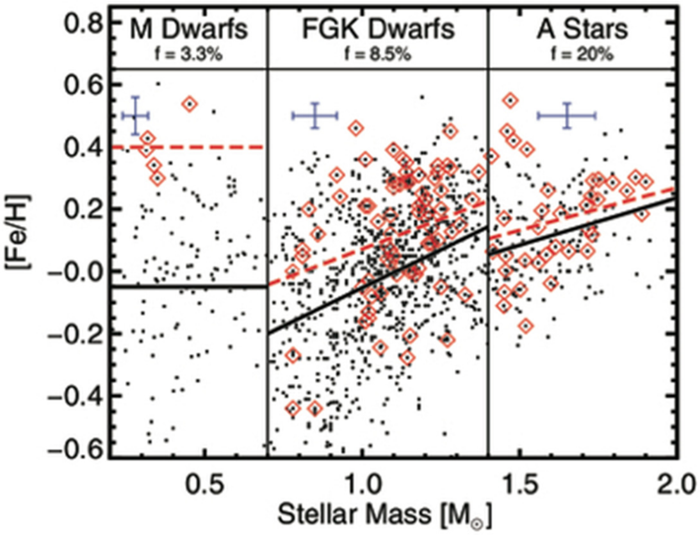

FIGURE 2.2 The black dots show the stellar mass versus metallicity of the entire sample of RV targets of Johnson et al. (2010). The systems that host at least one detectable planet are indicated by red diamonds. The sample has been subdivided into three broad groups according to stellar mass: M dwarfs, FGK dwarfs, and massive "retired" A stars. The fraction *f* of stars with planets is printed above each group. The thick black lines in each stellar mass group represent the best-fitting linear relationships between mass and metallicity; for the M dwarfs, the lines represent only the difference in metallicity between the planet-hosting and non-planet-hosting sample. The dashed red line is the best-fitting linear relationship between mass and metallicity for the stars with planets. The blue two-dimensional (2D) error bars represent the typical measurement uncertainties. SOURCE: Johnson et al. (2010).

Transits

The transit method has become the most productive exoplanet detection technique since the last decadal survey. NASA's Kepler mission played a key role in this revolution by performing a sensitive survey of exoplanets that spanned a wide region of parameter space. Owing to the large number of stars it monitored, the exquisite relative photometric precision it achieved on those stars, and the fact that it monitored the same set of stars for nearly 4 years, Kepler was sensitive to planets as small as Mercury in orbits of a few days (e.g., Barclay et al., 2013), and planets just over the size of Earth for periods of slightly less than one year (e.g, Thompson et al., 2018).

The primary results to emerge from Kepler's survey are as follows:

- Neptune-size planets (with radius less than four Earth radii, or $R_p < 4\ R_E$) in close-in orbits (much less than 1 AU) are common around Sun-like stars (Howard et al., 2012), confirming the result of Howard et al. (2010) and Mayor et al. (2011) and extending it to smaller masses.
- Roughly half of all stars in the galaxy have planets intermediate in size between Earth and Neptune that orbit closer than Mercury does to the Sun (Dressing and Charbonneau, 2015; Burke et al., 2015).
- There exist two distinct populations of small planets (see Figure 2.3; Fulton et al., 2017; Van Eylen et al., 2018). A planet radius gap (sometimes colloquially referred to as the "Fulton Gap") separates planets that are gas-rich and thus have larger sizes from likely rocky planets with thin or nonexistent atmospheres that have smaller sizes. The distribution of planets in terms of size and irradiation received supports the hypothesis that mass loss from photoevaporation sculpts the population of highly irradiated planets. This result also suggests that atmospheres of mini-Neptune-size planets are predominantly composed of nebular gas accreted from the protoplanetary disk, rather than heavier elements from outgassing or sublimation (Owen and Wu, 2017).
- There is approximately one habitable-zone terrestrial planet (1-1.5 R_E) for every 4 M-dwarf stars (Dressing and Charbonneau, 2015). For Sun-like stars, there is at least one habitable-zone terrestrial planet (0.8-1.2 R_E) for every 10 stars (Burke et al., 2015), although this estimate is based on an extrapolation and significant uncertainties remain.

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FIGURE 2.3 The frequency of planets around Sun-like stars with orbital periods <100 days as measured by Kepler. The bimodal distribution indicates two distinct populations of planets—for example, those that are primarily rocky with very thin atmospheres, and those that have substantial atmospheres, which are separated by a gap. SOURCE: Fulton et al. (2017).

The constraints on the frequency of terrestrial planets in the habitable zones of Sun-like stars are less certain than the corresponding planet frequency of such planets orbiting M dwarfs. This is due to several factors, including (1) the fact the signal of a terrestrial planet transiting an M dwarf is much larger than the signal of a terrestrial planet transiting a Sun-like star, and (2) the fact that planets in the habitable zones of low-mass stars (M dwarfs) have shorter periods. These factors, when combined with the fact that the duration of the primary Kepler mission was only roughly 3.5 years, and the higher than expected stellar noise of the Kepler targets, made it much easier to detect terrestrial planets in the habitable zones of M stars than Sun-like stars, and thus the estimates of the frequency of such planets is much more reliable. Nevertheless, researchers have high confidence that terrestrial planets orbiting in the habitable zones of Sun-like stars are relatively commonplace (Burke et al., 2015).

Therefore, for the first time, researchers are in a position to design the next set of experiments aimed at characterizing these kinds of planets to determine their atmospheric compositions and temperatures and to search them for signs of life.

The next step to characterizing the atmospheres of potentially Earth-like planets is to find such objects around the nearest stars. The search for characterizable Earth analogues around G dwarfs remains work for the future and so is discussed later in this report. However, the search for characterizable Earth analogues around M dwarfs is already underway and yielding important successes.

Ground-based transit searches focused exclusively on mid- to late M dwarfs—for example, MEarth, Transiting Planets and Planetesimals Small Telescope (TRAPPIST)/Search for Habitable Planets Eclipsing Ultra-Cool Stars (SPECULOOS)—are an important complement to broad surveys like Kepler and the recently launched Transiting Exoplanet Survey Satellite (TESS) mission (see the section "Planet Discoveries Through Transits," in Chapter 4). As an example, such surveys have already found two compelling systems of habitable-zone, Earth-size planets for follow-up characterization. The two systems are TRAPPIST-1 (Gillon et al., 2017) and LHS1140 (Dittmann et al., 2017). TRAPPIST-1 is a system of seven small transiting planets, with three of them in and near the habitable zone (see Figure 2.4). The TRAPPIST-1 planets show a surprising range of densities, and thus a range of volatile and gas fractions that indicate a complex history of planet formation. LHS1140 hosts two transiting planets with densities consistent with an Earth-like composition, one of which lies in the habitable zone. Both the TRAPPIST-1 and LHS1140 systems are expected to be touchstones for exoplanet characterization studies with the James Webb Space Telescope (JWST) due to their favorable planet-to-star radius ratios and infrared bright host stars. The relative ease with which these planets were detected also suggests that many more of these systems are waiting to be discovered.

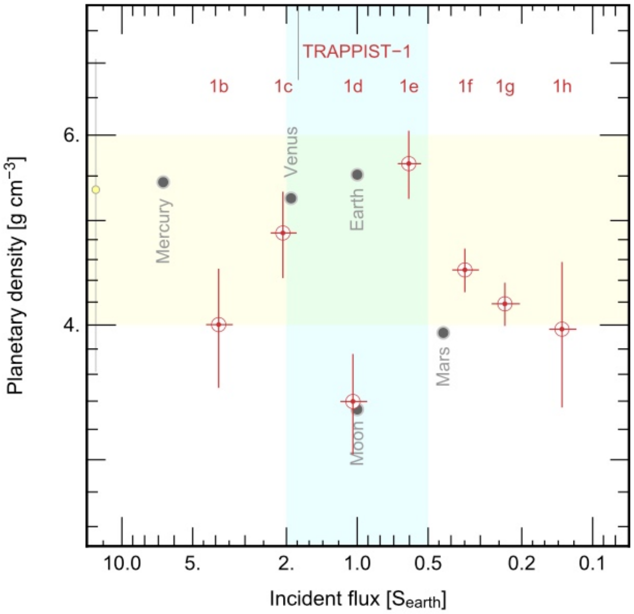

FIGURE 2.4 Densities of small transiting exoplanets and the Solar System terrestrial bodies relative to the incident flux they receive. The TRAPPIST-1 planets are highlighted in red. An optimistic range for the habitable zone is shown in light teal shading, and a notional range of habitable planet densities is shown as the yellow shading. SOURCE: Grimm et al. (2018).

Direct Imaging

The earlier generation of young-planet direct imaging surveys were primarily sensitive to massive (>5 M_J) planets or those in very wide (>100 AU) orbits. Relatively few detections were made from these surveys, implying an occurrence rate of 0.001-0.013 planets per star with parameters in the range of 5-13 M_J and 30-300 AU (Bowler, 2016). However, detections by the current generation Gemini Planet Imager (GPI) and Spectro-Polarimetric High-Contrast Exoplanet Research (SPHERE) instruments indicate that the occurrence rate of giant planets may increase somewhat at smaller separations, perhaps rising, as expected, to meet the Doppler occurrence rate at 5-10 AU.

Completion of the Gemini and SPHERE surveys should help narrow these constraints. There are several important caveats in any of these statistics. Young-planet imaging is very sensitive to the very steep mass-luminosity relationship for the planets, such that a significant population of Jovian-mass planets would be nearly undetectable. Second, the mass-luminosity relationship is very sensitive to initial entropy of formation (Marley et al., 2006; Spiegel and Burrows, 2012), which in turn is sensitive to their formation pathway; planets that accrete most of their mass through a narrow shock—which would happen in the classic Jupiter formation scenario—may have much lower initial luminosities and be nearly undetectable with current technology. The imaged giant planets with dynamical mass constraints (Beta Pictoris b and HR8799bcde) are inconsistent with low-luminosity formation. It is possible that distinct formation mechanisms operate for giant planets in wide (>10 AU) orbits (Toomre, 1964; Boss, 1998; Gammie, 2001; Rafikov, 2005; Kratter et al., 2010).

Microlensing

The primary strength of the microlensing technique is to determine the demographics of exoplanets, particularly those beyond the snow (or ice) line, the location in the protoplanetary disks where water ice is stable. Since it is generally believed that terrestrial planets that formed in the habitable zones of their parent stars largely formed without significant amounts of water, it is of great interest to understand how water (or volatiles in general) may have been delivered to terrestrial planets in the habitable zone.

To date, ground-based surveys for planets beyond the snow line have reached the following conclusions (most of which are summarized graphically in Figure 2.5):

- For cold planets orbiting M dwarfs, low-mass planets (with the mass of roughly that of Neptune or lower) are much more common than giant planets (Gould et al., 2006).
- The mass function of cold planets orbiting M dwarfs with planet/star mass ratio greater than roughly 2×10^{-4} (similar to the mass ratio between Neptune and the Sun) is significantly steeper than the mass function of warm planets in the same mass-ratio regime orbiting solar-type stars.
- Giant planets (with mass greater than 30 M_E) are not rare among M dwarfs (Clanton and Gaudi, 2014, 2016), at least for long orbital periods, although they are rarer than giant planets in the same mass range orbiting solar-type stars.
- The frequency of planets with the mass of Jupiter or greater orbiting M dwarfs found by microlensing is roughly 3 percent, consistent with that found by radial velocity surveys of M dwarfs for planets with separations of greater than a few AU (Clanton and Gaudi, 2014).
- Among cold planets orbiting M dwarfs, Neptune-mass objects may be most common (although super-Earth-mass planets may be comparably abundant; see Figure 2.5). Even so, the absolute abundance of cold super-Earths is substantial and similar to with the frequency of the best known super-Earth population, warm super-Earths orbiting solar-type stars.

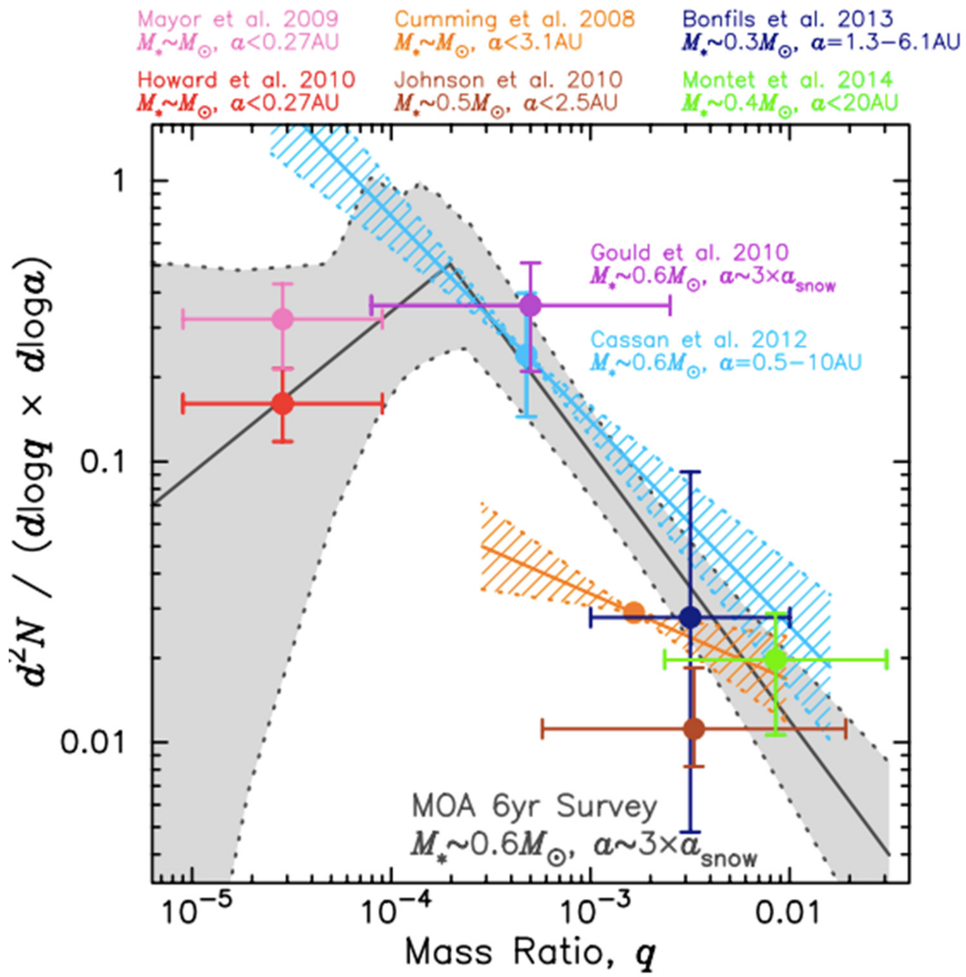

FIGURE 2.5 A broken power-law fit to the frequency of planets per log mass ratio *q* per log semimajor axis *a*, as a function of planet/star mass ratio *q,* as measured by the Microlensing Observations in Astrophysics (MOA) microlensing survey, is shown as the black dotted line. The uncertainty around this fit is shown as the gray shaded region. This frequency is compared to several other results on the frequency of planets in this plane using various methods and for various ranges of mass ratio and semimajor axis, as labeled. SOURCE: Suzuki et al. (2016).

Disk Properties

The last decade has seen remarkable progress in elucidating the average and range of properties of disks through both imaging and spectroscopy. The number of spatially resolved disks has increased from a handful to hundreds, thanks to a combination of scattered light observations from the Hubble Space Telescope (HST) and large, adaptively corrected ground-based telescopes, mid-infrared (MIR) emission resolved with the ground-based telescopes, Spitzer, the Herschel Space Telescope, and far-infrared emission from the Atacama Large Millimeter/submillimeter Array (ALMA). Properties such as surface density and composition can now be probed within disks, and structures can be related to planet formation processes.

ALMA surveys of nearby star-forming regions confirm previously known results with much better fidelity and are teasing out the details of the physical and chemical characteristics of disks. Some important recent results that set the time scale and composition relevant to planet formation are

- Disk mass correlates with stellar mass, albeit with substantial scatter at any given stellar mass (e.g., Andrews et al., 2013; Barenfeld et al., 2016; Pascucci et al., 2016; Ansdell et al., 2017).
- Disk dissipation occurs quickly, so that by roughly 3 Myr, half of stars do not have measurable dust emission (e.g., Haisch et al., 2001; Fedele et al., 2010; Ribas et al., 2014; Richert et al., 2018).
- The initial growth of solids, from the roughly 0.1 micron size characteristic of the interstellar medium to the 1 cm size and larger, occurs quickly, probably while the star is still accreting from its primordial envelope (Testi et al., 2014). Associated theoretical work has shown that planetesimals can form quickly following grain growth with turbulent dust concentration and self-gravity (see review by Johansen et al., 2014).
- Even at young ages (<3 Myr), disk masses as estimated from dust and gas tracers such as CO are lower than the Miminum Mass Solar Nebula (Ansdell et al., 2016; Eisner et al., 2018); most solids must already be in planetesimals or planets and gas must evolve rapidly.

ALMA, now in its fifth annual cycle of investigator-driven observations, has produced many novel results. In particular, ALMA observations have demonstrated that

- There exists a prevalence of gaps and other substructures at a wide range of separations in disks, as was first demonstrated by the striking observations by ALMA of HL Tau (see Figure 2.6). Whether these gaps can be attributed to planets, ice condensation fronts, dust trapping, or combinations of these and other mechanisms is not yet known.
- Observations of tracer molecules provide direct evidence for the water ice snow line (e.g., Qi et al., 2013).
- Complex organic chemical pathways are operating in disks, as inferred for the Solar System (e.g., Oberg et al., 2015).
- Disks inherit the isotopic ratios from molecular clouds in which they were born (Hily-Blant et al., 2017), and also demonstrate their changing chemistry due to stellar and interstellar irradiation (Cleeves et al., 2017).
- Outer disks have low turbulence (Flaherty et al., 2017, 2018); this is at odds with the magnetorotational instability (MRI) mechanism that has been successful in explaining accretion rates of inner disks onto the star.

There are likely many more advances to come from ALMA spectroscopy of gas and imaging of dust continuum. Observations of both dust and gas indicate that pressure bumps in disks can be created and influence the migration of solids; the buildup of icy or dry pebbles may determine if a planet is a water world or a rocky terrestrial planet. Scattered light observations of disks, from HST and large ground-based telescopes, provide complementary information on the disk structure by tracing small grains, so that greater constraints may be placed on the dynamics induced by any young planets (e.g., Debes et al., 2017; Avenhaus et al., 2018).

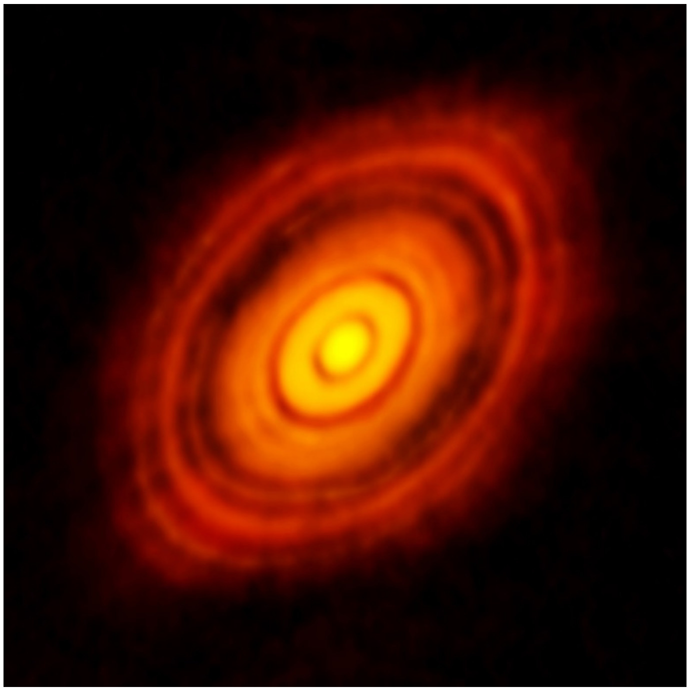

FIGURE 2.6 ALMA submillimeter observations of the protoplanetary disk surrounding HL Tau, displaying many gaps and rings from 13-100 AU, whose physical cause is currently under debate, but may be due to grain growth, planetary sculpting, or ice condensation. SOURCE: ALMA Partnership et al. (2015).

From Disks to Planets

Population synthesis models try to tie what researchers know about the initial conditions of planet formation, as deduced from studies of circumstellar disks described in more detail below, with the observed exoplanet demographics. There have been many attempts at such synthesis, and they generally serve to highlight the major unknowns. Examples include the following:

- The recent idea of "pebble accretion" enables rapid growth of gas giant cores (e.g., Ormel and Klahr, 2010; Lambrechts and Johansen, 2012) but also make the growth rates subject to many unknown disk properties such as the dominant sizes of solids as a function of distance from the star, turbulence, evolving gas-to-dust ratio, and feedback in the disk pressure structure between the forming planets and the disk gas.
- The rate of migration of gap-opening planets (Type II migration) is uncertain due to the uncertainty in how the local disk mass changes self-consistently around a migrating planet (Lin and Papaloizou, 1986; Durmann and Kley, 2017).
- The rate of disk dispersal and the radial profile of disk dispersal change the migration rates of planets (Alexander and Pascucci, 2012; Ercolano and Rosotti, 2015; Wise and Dodson-Robinson, 2018; Jennings et al., 2018).
- The physics of mass accretion onto a giant planet determines how fast the planet can build up mass and feeds back into migration rate (Alessi and Pudritz, 2018).
- Dynamical instabilities late in planet formation may change the final distribution of planets (Carrera et al., 2018).

Debris disk observations reveal structures such as rings, warps, and asymmetries that highlight the complicated dynamics of young planetary systems and the importance of collisions between large planetesimals in the first 100 Myr of planetary evolution (Hughes, 2018). Many more debris disks have been found with gas; some planetesimals that survive to the debris disk phase are extremely volatile rich (e.g., Moór et al., 2017; Kral et al., 2017). While debris disks around M stars are rare or have very low surface densities, the complex variation of the AU Mic disk suggests that stellar winds are very important in driving disk dynamics (Boccaletti et al., 2015); such winds could also have profound impacts on close-in planets.

Disks around mature stars cannot be primordial but rather need to be generated by the evaporation and collisions of planetesimals. Their presence signals that planet formation proceeded at least to the point of making planetesimal belts.

- The dust mass in debris disks decays with time, such that detectable disks are much more common around stars with ages <100 Myr than around stars of solar age, but roughly 20 percent of field stars appear to host cold disks more massive than that of the Solar System (Montesinos et al., 2016).
- Most debris disks are composed of cold rings, and therefore some dynamical process removed planetesimals from some portions of the circumstellar environment but left or shepherded belts in others.
- There is no evidence for a strong correlation between the presence of a certain type of disk and the type or location of inner planets (Moro-Martín et al., 2015; Wittenmyer and Marshall, 2015; Meshkat et al., 2017), although there are some exceptions (e.g Dawson et al., 2011; Wilner et al., 2018).
- It appears that most debris disks with warm inner dust also have cold outer dust, but the physical connection between the two is unclear (Ertel et al., 2018).

At the time of the last decadal survey in astronomy, uncertainty in the amount and distribution of exozodiacal dust was considered a key issue in planning a future direct imaging mission. Much progress has been made on this topic (see review by Roberge et al., 2012) from Spitzer, the Wide-field Infrared Survey Explorer (WISE), the Keck Interferometer and, most recently and sensitively, the Large Binocular Telescope Interferometer (LBTI). Sun-like stars with no known cold dust rarely have dust in their habitable zones, with an upper limit of ~26 zodis (Ertel et al., 2018).

Exoplanet Atmospheres and Interiors

Polluted White Dwarfs

One of the only constraints on the compositions of extrasolar planetesimals comes from observations of white dwarfs with metal lines created by the accretion of planetary material that survived the post-main sequence evolution of the star. A major conclusion of many studies is that extrasolar planetesimals have compositions similar to the Solar System's terrestrial planets (see the review of Zuckerman and Young, 2017).

Bulk Composition and Interior Structure from Transits

Exoplanet bulk compositions can be probed by comparing measurements of planetary masses and radii to theoretical models. Figure 2.7 shows the data for the 418 transiting exoplanets with fractional measurement errors less than 20 percent in both mass and radius, the vast majority of which are on close-in orbits (*a* < 0.1 AU) and orbit mature stars. Key results from this data set are as follows:

- The observed diversity of planetary radii for a given mass generally implies significant variations in bulk composition.
- Most close-in Jovian-mass planets have radii larger than Jupiter, in some cases twice that of Jupiter. These so-called inflated hot Jupiters need to be hydrogen-dominated objects like Jupiter and Saturn. The mechanism by which these planets have been "inflated" has eluded a definitive explanation (Thorngren and Fortney, 2018), although it is clear that the high levels of irradiation that most of these planets receive from their host stars need to play a role.
- The existence of Jovian-mass objects that lie below the hydrogen-helium model curve implies that some giant exoplanets need to have enhancements of heavy elements relative to Jupiter and Saturn.
- The variations in the sizes of transiting Jovians with more moderate levels of irradiation than the majority of the sample indicates that the planetary heavy element abundances are correlated with the metallicities of the stellar hosts (Thorngren et al., 2016).

The tendency of lower mass planets to have smaller sizes indicates that the trend of increasing heavy element abundance for lower mass planets seen in the Solar System also roughly holds for exoplanets. These intermediate-size planets are likely composed of some combination of iron, rock, ice, and gas, with the precise ratios unknown due to the existence of inherent degeneracies in interior structure models when only the mass and radius are known (Adams et al., 2008). It is thought that observational constraints on atmospheric composition can be used to break these degeneracies (Miller-Ricci et al., 2009), but attempts to date have been stymied by the difficulty of getting precise atmospheric metallicities for planets in this regime. The committee anticipates that JWST will yield a transformative breakthrough in this area.

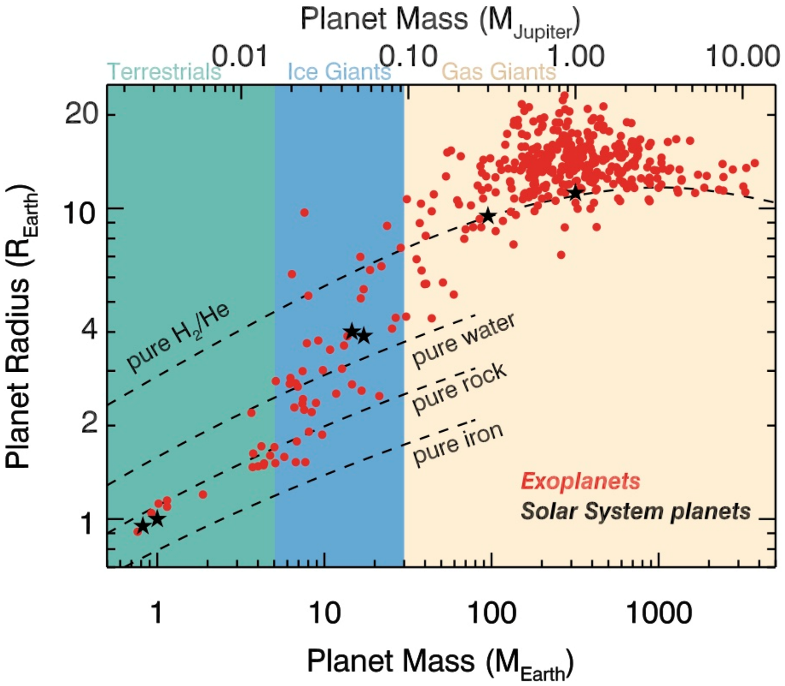

FIGURE 2.7 Masses and radii for the 418 transiting exoplanets with fractional measurement errors less than 20 percent (red circles, NASA Exoplanet Archive). The Solar System planets are indicated by black stars. The dashed lines show the predictions in Fortney et al. (2007) of theoretical models for simple compositions.

Definitively low-mass (mass less than 10 M_E) planets have been identified at increasing rates in recent years. From the systems discovered to date, it is known that

- Truly terrestrial ("rocky") planets have compositions that are remarkably consistent with a precisely Earth-like composition (e.g., Dressing et al., 2015), although it remains to be seen if this is an artifact of small sample sizes and large uncertainties.
- There is an unexpected apparent overlap between terrestrial super-Earths and volatile- or gas-rich mini-Neptunes in the mass range 1-10 M_E (Hadden and Lithwick, 2017); this discovery suggests that there is not a single threshold mass at which planets can efficiently accrete gas, and that low-mass planets are not guaranteed to be rocky.
- There appears to be a critical size below which planets are likely mostly rocky. Mass-radius data indicate that this turning point is around 1.6 R_E (Rogers, 2015), which is consistent with the location of the radius gap described above, although there is significant evidence that this is not a sharp transition (Wolfgang et al., 2016). The frequency of small planet sizes and the distribution of mass-radius values together provide a path for homing in on rocky planets, using the measurement of planetary radii (Lopez and Fortney, 2014).

It should be emphasized that the mass-radius diagram in the small planet regime is highly biased toward planets on very short period orbits and the more massive versions of planets for a given size because these are the easiest planets to detect, and the data set is highly heterogeneous in terms of relative precision on the measurements, host star type, semimajor axis, and so on. Further exploration of the mass-radius relationship for small planets that accounts for these complexities using discoveries from NASA's recently launched TESS mission discoveries is highly anticipated.

Exoplanet Atmospheres from Time-Series Techniques

The geometry of transiting planets also permits observations of their atmospheres (see Figures 2.8 and 2.9). During planetary transits the so-called transmission spectrum is measured by determining how the apparent size of the planet varies with wavelength. The combined light from a planetary system also includes the reflected (typically dominant in the optical) and emitted light (typically dominant in the infrared) from a planet. This can be probed just around secondary eclipse to measure a planet's dayside spectrum as it disappears behind its host star, or during larger fractions of the planet's orbit to measure the its phase curve. Combined light measurements of planetary spectra can be obtained for nontransiting planets using the same time-series techniques, although the absolute flux is unknown without observations of a secondary eclipse. Transmission spectra can only be obtained for transiting planets.

Exoplanet atmosphere observations with time-series techniques have been very successful over the last two decades, despite that fact that none of the instruments that were used were designed specifically for these measurements. Such observations are challenging because planetary signals are 10^{-3} that of their host stars or smaller. Systematics typically dominate the raw data at this level, and thus stringent control of these systematics via careful calibration is an essential requirement in extracting reliable inferences. Signals down to the 10^{-4} level have been detected, and signals at the 10^{-5} level will be sought moving forward. The current state of the field is that it is strong and poised for major discoveries with upcoming facilities.

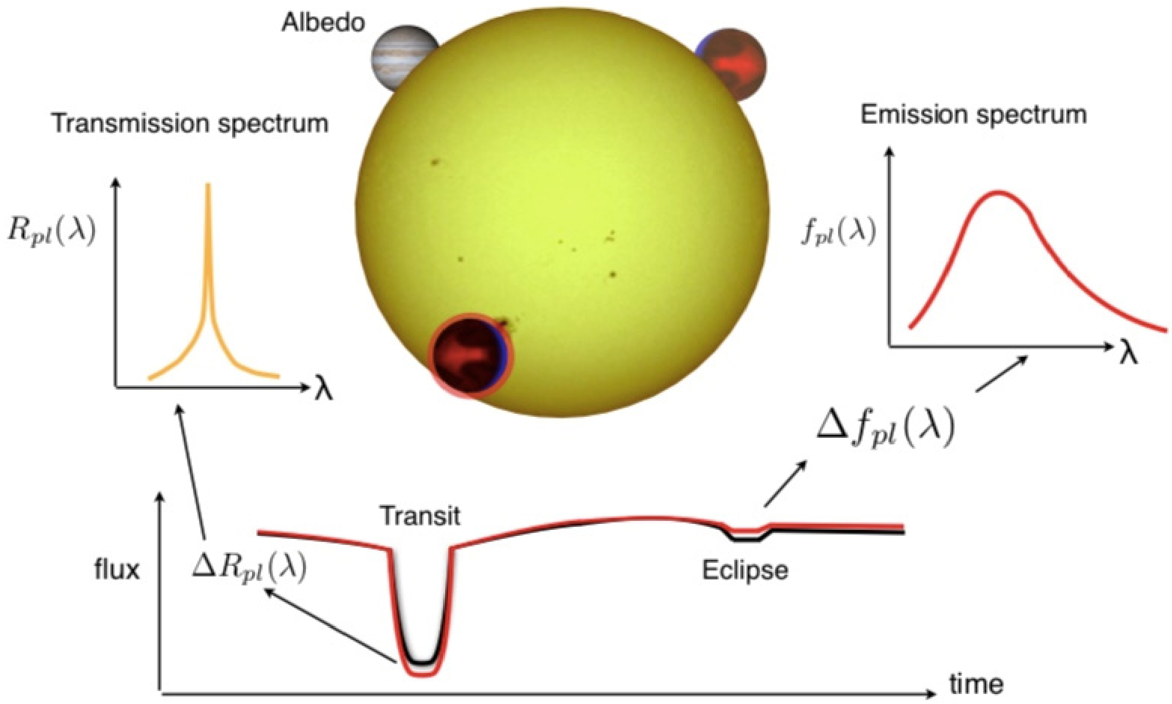

FIGURE 2.8 Illustration of the probes of transiting exoplanet atmospheres. During transit one observes the transmission spectrum, which is a measurement of the apparent planet size with wavelength. Absorption makes the planet appear larger in the transmission spectrum. The spectrum of the planet, reflected and emitted, is measured from the combined light of the system at all phases. The absolute planet flux is referenced to the brightness of the system during secondary eclipse when only the light from the host star is observed. SOURCE: Sing et al. (2018).

Successful exoplanet atmosphere observations using time-series techniques have been made with a wide range of instruments, both ground- and space-based observations, and over wavelengths ranging from X-rays to the mid-infrared. These observations have led to the detection of many gas phase chemical species (e.g., H_2O, CO, Na, K, H, and He) and constraints on temperatures as a function of pressure, longitude, and latitude (for a recent review, see Deming and Seager, 2017). These results have led to a wide range of findings about the composition, chemistry, and physics of exoplanet atmospheres. Some highlights include the following:

- Determination of water abundances as a tracer of the underlying elemental abundances in numerous exoplanets, and the connection of this marker to planet formation (e.g., Kreidberg et al., 2014);
- The discovery that aerosols are prevalent in exoplanet atmospheres (e.g., Sing et al., 2016; see Figure 2.7, earlier);
- The mapping of exoplanet temperatures with phase curve observations and the resulting constraints on energy transport in highly irradiated atmospheres (e.g., Knutson et al., 2007);
- Observations of planetary evaporation (e.g., Vidal-Madjar et al., 2003); and
- The advance of the high-dispersion spectroscopy technique as a unique ground-based tool for detecting exoplanet atmospheres and probing their compositions and dynamics (e.g., Snellen et al., 2010).

Permission Pending

FIGURE 2.9 An atlas of transmission spectra for 10 hot Jupiters obtained with HST and Spitzer. Absorption from a variety of chemical species including H_2O, Na, and K along with scattering from aerosols are common. SOURCE: Sing et al. (2016).

Similar to the overarching picture that has emerged from the mass-radius diagram of exoplanets, the overarching picture of exoplanet atmospheres is that they display a surprising variety of chemical compositions, thermal structures, energy budgets, and heat transport efficiencies. Therefore, it has been challenging to discern the low-order trends in atmospheric properties as a function of planetary properties (e.g., atmospheric metallicity versus planet mass) that are expected from theory. It is difficult to say at this point how much intrinsic planetary variation, limited measurement accuracy and precision, modeling degeneracy, and the inherent complexities of atmospheres each play a role in this lack of clarity. What is clear is that the expanded capabilities of upcoming facilities like JWST and the giant segmented mirror telescopes (GSMTs; see the section "Ground-Based Studies," in Chapter 4) will bring transformative data to bear on these issues.

Exoplanet Atmospheres from Direct Imaging

As discussed above, current direct imaging techniques are limited to young, self-luminous, giant planets. However, since they are spatially resolved from their parent star, it is relatively straightforward to obtain near-infrared spectra of these planets. These spectra have led to the following results and conclusions:

- The spectra of these young giant planets resemble similar but higher-mass brown dwarfs. Indeed, they show the same overall features—water and carbon monoxide at higher temperatures (Konopacky et al., 2013) and methane features at lower temperatures (Macintosh et al., 2015).
- Interpretation of these spectra, as with transit spectroscopy, is model dependent; in particular, the emergent spectrum is very sensitive to properties of the thermally emitting cloud layer in the planet's atmosphere (Figure 2.10).
- These clouds have distinct properties from the high-mass brown dwarfs, in that they persist to lower (<700 K) temperatures.
- The probed photospheres are significantly out of chemical equilibrium, likely due to vertical circulation. In turn this makes extraction of elemental abundances challenging.
- Planets are consistent with Sun-like to somewhat enhanced carbon to oxygen ratios (Barman et al., 2015) and solar to somewhat enhanced overall metallicity (Rajan et al., 2017), although no clear trend with mass or separation can be detected.
- Planetary rotation periods have been determined for several planets, and are similar to that of Jupiter (Snellen et al., 2014; Bryan et al., 2018).

Higher resolution spectra and improved models should allow researchers to determine if giant planet composition varies from the inner solar systems probed by transit techniques to the outer wide-orbit planets seen in imaging.

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FIGURE 2.10 Spectrum and photometry of the young (25 Myr) giant (2-3 M_J) planet 51 Eri b compared with several models. While general features match, no model fit is particularly compelling—in addition to significant residuals, all appear to overestimate the planet's effective temperature and underestimate its radius compared with evolutionary models. SOURCE: Rajan et al. (2017).

Moderate-resolution (R = 50-100) spectroscopy of mature giant planets, combined with atmospheric-retrieval modeling, can determine atmospheric molecular abundances and provide insight into formation processes (Lupu et al., 2016). For example, planets that formed through global disk instabilities may have stellar-like abundances, although it should be noted that post-formation accretion of planetesimals may substantially change the elemental abundance ratios even for these objects (Thorngren et al., 2016). Planets that have migrated may retain element ratios indicative of their original formation zone (e.g., Oberg, Murray-Clay, and Bergin, 2011). Validating these techniques by practicing first on giant planets will also increase confidence in their application to Earth-like worlds.

The Search for Life on Exoplanets

Impact of Host Star Properties

The vast majority of the photons observed in exoplanetary systems originate from the host star, and not from the planet. In fact, the most fruitful planet detection techniques to date, and for the immediate future, are the transit and RV methods, both of which are indirect detections of exoplanets as observed through the influence of the planet on the host star. Thus, the ultimate precision and accuracy with which planet properties can be measured is governed by the precision and accuracy with which the properties of host stars can be measured.

The RV and transit exoplanet detection methods rely on measuring or inferring the mass or radius of the host star in order to estimate the mass and radius of the planet. Up until quite recently, measuring the mass or radius of an (effectively) isolated star has been either difficult or impossible. However, with the launch of Gaia, which provides both exquisite parallaxes of bright stars (roughly 10 microarcsecond precision for V < 12) along with all-sky surveys that have obtained broadband absolute photometry of stars over a broad wavelength range covering the majority of their spectral energy distributions (SEDs) from the near ultraviolet to the near-infrared, it has now become possible to estimate the mass and radius of relatively bright (V < 12) stars with low-mass transiting companions (e.g., single-lined spectroscopic binaries) with excellent precision (Stevens et al., 2018). The broadband photometry, combined with stellar atmosphere models, can be used to estimate the (unextincted) bolometric flux. Combined with an estimate of the stellar effective temperature from the spectral energy distribution (SED) or high-resolution spectra, it is possible to measure to radius of the stars essentially empirically to sub-1 percent levels (Stevens et al., 2018). The transit constrains the density of the star to exquisite precision (Seager and Mallen-Ornelas, 2003), and thus both the mass and radius of the host star and their transiting planets can be directly constrained (Stassun et al., 2017; Stevens et al., 2018).

Intrinsic stellar variability, including the effects of stellar flaring and modulated surface heterogeneities, can have detrimental effects on measuring the mass of a planet with RVs and its radius if it transits its star. The same fact is true across the entire wavelength range, although the impact is generally greater at shorter wavelengths, ranging from 50 percent overestimate in radii of giant planets orbiting Sun-like stars in the X-ray (Llama and Shkolnik, 2015), to a few percent in the infrared for small planets orbing M dwarfs (Rackham et al., 2018).

As discussed, there is great emphasis in detecting the planet's atmosphere and measuring its composition through transmission and emission spectroscopy. As these techniques are applied to smaller and smaller planets around more and more active stars, such as M dwarfs, imperfect knowledge of the central star grows in importance, as it often becomes the limiting factor in the detection of small planets, and if detected, in the precision with which the planet's mass, radius, and, thus, its density and spectrum, can be measured.

In addition to the challenges that stellar variability and heterogeneities produce for the accurate measurement of planet spectra, the high-energy radiation (10-300 nm) from the upper stellar atmosphere—namely, the chromosphere, transition region, and corona—directly alters the temperature and chemistry of the planet's atmosphere of all types of exoplanets, from Earth's to Jupiter's (Figure 2.11). For terrestrial planets, including those in the habitable zones of low-mass stars, this radiation has the potential to strip the planet atmosphere completely, or to generate hazes, two scenarios that result in a flat transmission spectrum of a rocky planet. Should the planet atmosphere survive and be haze-free, the ultraviolet stellar light can alter the planet's photochemistry in several ways, potentially creating false positive and even false negative biosignatures.

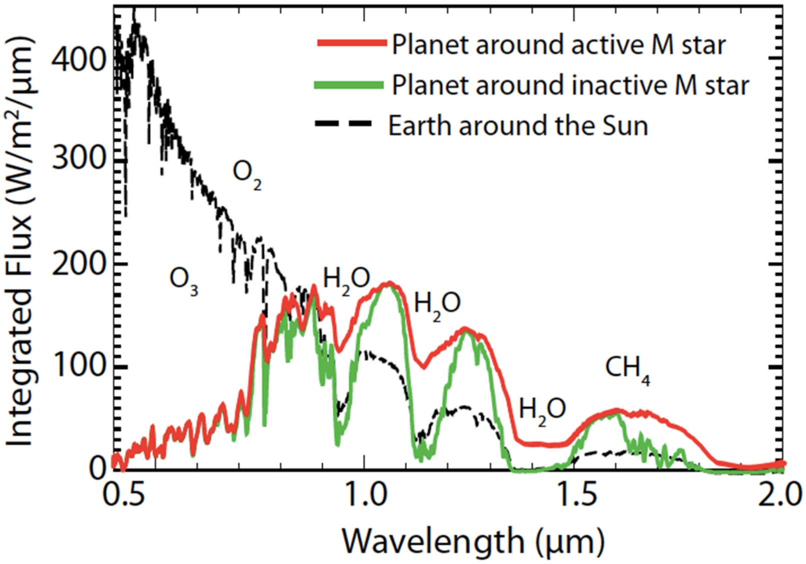

FIGURE 2.11 The stellar UV flux has a dramatic effect on a planet's atmospheric content. The plot shows an Earth-like planet spectrum in the habitable zone of an active (red) and extremely inactive (green) M4 dwarf. The spectrum of Earth around the Sun is shown in black for comparison. SOURCE: Adapted from Rugheimer et al. (2015).

Astrobiology

In the last 10 years, exoplanet astrobiology has transformed from a field driven by promising statistical predictions into one with nearby targets accessible to near-term observation. Over this time, astrobiology research that supports the search for life on exoplanets has advanced in two major areas: (1) the development of exoplanet habitability assessment as an interdisciplinary multiparameter concept including planetary and stellar properties and planet-star-planetary system interactions, and (2) in enhancing confidence in biosignature assessment for more reliable biosignatures like O_2, while proposing new exoplanet biosignatures that may broaden the search. A biosignature is a global impact of life on its planetary environment that may be detectable at interstellar distances, and so likely requires a surface ocean supporting a surface biosphere (Des Marais et al., 2002; Schwieterman et al., 2018). This detectability requirement also drives the definition of a habitable zone for exoplanets to be that region around a star where a planet with an Earth-like atmosphere can maintain liquid water on its surface (Kasting et al., 1993; Barnes et al., 2009; Kopparapu et al., 2013).

Biosignature science has recently advanced three major new areas of research:

- An in-depth evaluation of O_2 as a potential biosignature that identified additional gases and other environmental context to strengthen researchers' ability to discriminate between abiotic

and biological production of O_2. This has greatly increased the ability to identify O_2 a reliable indicator of life.
- Building on the detailed treatment of O_2, the community has taken the first steps toward the development of a comprehensive framework that can be used to interpret other potential biosignatures in the context of their environment, and similarly increase confidence that they are indeed due to life.
- The search for and identification of new potential biosignatures, especially those that may permit detection of non-Earth-like metabolisms.

From Demographics to Habitable Zone Targets

The Kepler mission has revolutionized knowledge of the frequency of potentially habitable worlds, particularly around low-mass stars. Recent discoveries of nearby potentially habitable planets using ground-based observations (Anglada-Escudé et al., 2016; Gillon et al., 2016, 2017; Dittmann et al., 2017) have ushered in new era of comparative planetology for potentially habitable zone (HZ) planets. A bevy of resources are being trained on these planets in order to measure their detailed properties, including radii and masses (Gillon et al., 2017; Grimm et al., 2018; Dittman et al., 2017), to determine if they are rocky.

Whether M dwarfs can host habitable planets is an interesting question that is still open for debate (Shields et al., 2015; Kaltenegger et al., 2017). In particular, the long superluminous pre-main sequence phase of M dwarf hosts may drive initial strong atmospheric and ocean loss (Ramirez and Kaltenegger, 2014; Luger and Barnes, 2015), potentially resulting in oxygen- or carbon dioxide-dominated atmospheres for planets in the habitable zone (Luger and Barnes, 2015; Tian, 2015; Meadows et al., 2018a). Initial attempts to probe the atmospheric composition of small habitable zone planets with the Hubble Space Telescope, the Spitzer Space Telescope, and ground-based telescopes (Delrez et al., 2018; deWit et al., 2018; Southworth et al., 2017) have provided only broad constraints that rule out hydrogen-dominated atmospheres. In the next 5-10 years, TESS will find more nearby transiting HZ planets (Sullivan et al., 2015; Barclay et al., 2018), and JWST and the GSMTs will search for and characterize high-molecular weight atmospheres, providing the first glimpses into the atmospheres of potentially habitable planets. These new observations will enable the first, albeit challenging, search for signs of life on nearby worlds, and test researchers' understanding and models of habitable planetary environments and processes.

What Makes a Planet Habitable?

In parallel with the advances in observations, the exoplanet, Solar System, and astrobiology communities have generated a more comprehensive picture of planetary habitability. Unlike Solar System worlds where subsurface and sparsely inhabited environments (e.g., those that only have low levels of microbial life) could be probed by in situ spacecraft, for exoplanets this report considers only global or large-scale surface habitability that is potentially accessible to telescopic remote-sensing.

Many factors and interactions are now expected to impact planetary habitability. These include the following:

- The presence and distribution of liquid water oceans on the planetary surface, which depends on initial volatile delivery, outgassing, and retention against ocean loss.
- The presence of a stable secondary atmosphere. It is believed that potentially habitable planets need to lose most or all of their primary H_2-dominated atmospheres (Owen and Mohanty, 2016; Pierrehumbert and Gaidos, 2011).

- The presence of tectonic or volcanic activity and weathering processes to replenish atmospheric loss (Lenardic et al., 2016), and buffer climate (Walker et al., 1981).
- The internal energy budget of a planet, which can be derived from the energy of formation and radionuclides (Frank et al., 2014; Young et al., 2014; Dorn et al., 2018; Unterborn et al., 2017), or from tidal energy deposition from gravitational interaction with the host stars or other planets (Jackson et al., 2008; Driscoll and Barnes, 2015).
- The presence and strength of a global-scale magnetic field, which depends on interior composition and thermal evolution (Driscoll and Bercovici, 2013).

There are important feedbacks identified between the processes listed above, which have been studied in limited cases. For example, the persistence of a secondary atmosphere over billion-year time scales requires low atmospheric loss rates, which in turn can be aided by the presence of a planetary magnetic field (Driscoll and Bercovici, 2013; Garcia-Sage et al., 2017; Dong et al., 2018).

Multiparameter Habitability Assessment

To support upcoming observations, and target selection for searches for life in particular, the astrobiology and planetary science communities have worked to identify characteristics and processes that enable planetary habitability and embrace a more interdisciplinary assessment framework. As useful as the habitable zone's first-order assessment of potential habitability has been for identifying that region around a star where a planet is more likely to be habitable (Kasting et al., 1993; Kopparapu et al., 2013), it is now understood that many factors, including those listed above, impact a planet's habitability. Consequently, efforts have begun to synthesize knowledge and observations from many different fields to provide a more comprehensive and powerful assessment of the likelihood of exoplanet habitability, thereby improving the ability to pick the best targets to search for life.

For example, whether M-dwarf habitable zone planets are indeed habitable is a key current question in astrobiology, with strong ramifications for the distribution of life in the galaxy, including in the Solar System neighborhood, due to the ubiquity of M dwarfs. M-dwarf planets may face significant impediments to habitability due to their energetic host stars, with perhaps the most significant challenge being the potential early loss of ocean and atmosphere due to stellar X-ray and extreme ultraviolet (XUV) radiation (Ribas et al., 2016; Luger and Barnes, 2015; Schaefer et al., 2016), and the stellar wind (Dong et al., 2017; Garcia-Sage, 2017). Conversely, even failure to lose a dense primordial (H_2-dominated) atmosphere may inhibit or preclude their habitability (Owen and Mohanty, 2016). Stellar UV and proton flux drive chemistry that continues to modify the planetary atmospheric composition (Segura et al., 2003, 2005; Rugheimer et al., 2015), which in turn impacts the planetary climate and surface UV protection (Segura et al., 2010; Rugheimer et al., 2017; Arney et al., 2017; Tilley et al., 2018), two important aspects of habitability.

Toward a Comprehensive Framework for Biosignature Assessment

Researchers' ability to search for life is constrained by the ability to recognize life's impact on its global environment, a biosignature. The presence of abundant O_2, or the simultaneous observed presence of O_2 (or O_3) and CH_4 (or N_2O) have traditionally been considered the highest priority biosignatures to search for, for reasons of both reliability and (relative) observability (see Appendix D for a summary of known biosignatures, their spectral features, and supporting observations for interpretation). These pairs of gases imply an atmosphere out of balance from chemical equilibrium, and they can be strong absorbers across the visible or infrared (IR) wavelengths.

However, the last 5 years have brought a rapid evolution in researchers' understanding of the complexity of biosignature interpretation and an impetus toward more rigorous standards of proof. Rather than being isolated phenomena, biosignatures are now understood to be highly influenced by the local planetary system environment, in which geological, atmospheric, and stellar processes interact and evolve to enhance, suppress, or sometimes mimic biosignatures. Consequently, the interpretation of the significance of the potential biosignature, rather than its measurement, is the most important process in life detection.

The field has so far focused on increasing the ability to interpret O_2 as a biosignature, and used geological constraints from the early Earth as well as photochemical and climate models to identify both false negatives (environmental processes that suppress the biological signal; e.g., Reinhard et al., 2017) and false positives (abiotic planetary processes that can mimic biosignatures) for O_2. These include several mechanisms for abiotic production of O_2 and O_3, for planets within the habitable zone (see Meadows, 2017, for a review). A summary of key components of this information is presented in Figure 2.12. An understanding of potential false negatives can inform the choice of environments for life searches that are least likely to suppress the biological signal, and knowledge of false positives can guide a comprehensive measurement strategy to rule them out and increase the credibility of the biosignature interpretation.

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FIGURE 2.12 False positives (abiotic planetary processes) for O_2 generation in extrasolar planetary atmospheres. This figure summarizes the atmospheric mechanisms by which O_2 could form abiotically at high abundance in a planetary atmosphere. The extreme left panel is Earth, the four panels to the right show the different mechanisms and their observational discriminants. Circled molecules, if detected, would help reveal a false positive mechanism. Failure to detect the "forbidden" molecules in the bottom shaded bar would also help to reveal the false positive mechanism. For example, on a habitable CO_2-rich M dwarf planet, the presence of CO and CO_2, and the absence of CH_4, is a strong indicator for a photochemical source of O_2 from the photolysis of CO_2. SOURCE: Meadows et al. (2018b).

Theoretical research into false positive mechanisms has also helped identify the potentially observable signals of abiotic production of O_2 or O_3 that might leave a detectable impact on the environment, or that result from characteristics of the parent star and the planetary environment. False positive discriminants so far identified include the presence of collisionally induced absorption from O_2 molecules that collide more frequently in dense, O_2-rich post-ocean-loss atmospheres (Schwieterman et al., 2016; Meadows et al., 2018b); CO from the photolysis of CO_2 (Schwieterman et al., 2016); lack of water vapor (Gao et al., 2015); lack of collisionally induced absorption from N_2 (Schwieterman et al., 2015b); and the absence of reducing gases like CH_4 (Domagal-Goldman et al., 2014; Meadows et al., 2018b). Biosignature interpretation therefore requires a suite of observations, rather than detection of a single molecule. Similarly, other characteristics that may enhance the interpretation of an atmospheric gas as a biosignature are also being considered and revisited, including additional biologically driven disequilibria (Krissansen-Totton et al., 2016), and secondary characteristics of a photosynthetic biosphere, such as surface reflectivity (e.g., the "red edge" of vegetation; Gates et al., 1965; Seager et al., 2005) or seasonal variations (Schwieterman et al., 2018; Olson et al., 2018).

Using the treatment of O_2 as a template, the community has started the development of a comprehensive framework that can be used to interpret other potential biosignatures in the context of their environment, and similarly increase confidence that they are indeed due to life, and not abiotic planetary processes. A comprehensive series of papers that reviewed the current state of the field and outlined this new assessment framework was published as part of a Nexus for Exoplanet Systems Science community-wide biosignatures workshop activity (Kiang et al., 2018; Schwieterman et al., 2018; Meadows et al., 2018a; Catling et al., 2018; Walker et al., 2018; Fujii et al., 2018).

Identifying Novel Biosignatures

While traditional biosignatures are the highest priority for biosignatures searches, recent research continues to identify new ideas for remote-sensing biosignatures, to potentially maximize the chances of recognizing alien biospheres. These newly proposed biosignatures include new atmospheric, surface, and seasonal biosignatures (see Schwieterman et al., 2018, for a recent review), and advances in a new area of research called "agnostic biosignatures." Research into the relative detectability of these newly proposed biosignatures is ongoing. Agnostic biosignatures are particularly exciting, as they are not identified as tied to a particular metabolism, but manifest as unexpected complexity in a system-wide alteration of a planetary environment, such as in its atmospheric chemistry (Walker et al., 2018). They may be the best chance of searching for non-Earth-like life. Novel promising potential biosignatures include the following:

- Seasonality in gas abundances, which may produce large features in the UV (Olson et al., 2018);
- The formation of hazes in anoxic environments, due to methanogenic production of CH_4 well above that expected from geological processes (Arney et al., 2018);
- The presence of ammonia on hydrogen-dominated worlds (Seager and Bains, 2015);
- The presence of an ocean, which may be detected in direct imaging, for a habitable world with an N_2/O_2 atmosphere (Krissansen-Totton et al., 2016); and
- The simultaneous presence of N_2, CH_4, CO_2, and liquid water for an early-Earth-type environment (Krissansen-Totton et al., 2018).

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3

Outlining the Exoplanet Science Strategy

CHARACTERIZING PLANETS AND PLANETARY SYSTEMS

Most if not all stars host planetary systems, but the structures of these systems and the properties of their planets are diverse (Chapter 2) and often unlike those of the Solar System. The physical and chemical processes that produce planetary bulk compositions, surfaces, and atmospheres are complex, and the guiding principles that determine the outcome have not yet been determined. One of the major goals of exoplanet science is as follows:

> **Goal 1:** 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.

To achieve this goal, the exoplanet science community needs to:

- Determine the range of planetary system architectures by surveying planets at a variety of orbital separations and searching for patterns in the structures of multiplanet systems;
- Characterize the diversity of bulk compositions and atmospheric compositions;
- Identify the parameters that determine which stars can form certain types of planetary systems; and
- Identify relationships between the planet formation process and the resulting planetary evolution, bulk composition, and atmospheric properties.

A key goal of the theory of planet formation is to produce population synthesis models that tie observationally constrained properties of stars and circumstellar disks to the observed population of planets. Major open questions in planet formation theory include: How do planetesimals with sizes of order kilometers to hundreds of kilometers form? Do all gas giants form through the core accretion process or is an additional population produced by gravitational instability? How does recent work demonstrating that gas drag can facilitate efficient accretion of pebble-size planetesimals change classic core accretion scenarios? What determines whether a planet grows to be a terrestrial, super-Earth, or giant planet? How do chemical transitions at the ice lines of abundant volatile species affect the compositions of planets that form at different distances from their stars? What determines whether planets undergo substantial migration? Broadly stated, how do the parameters of disks, including their masses, sizes, angular momenta, chemical structures, and dispersal time scales result in the diversity of planetary systems? Pursuing these questions requires an understanding of the distribution of both disk properties and planets.

Characterizing the population and properties of giant planets is central to this endeavor: giant planets dominate the dynamics and planetary mass of their host systems. To the extent that the population of gas giants has been constrained, it has already provided important clues to the physical parameters that control planet formation: For example, high metallicity stars are known to host more close-in giants (Gonzalez, 1997; Fischer and Valenti, 2005; Santos et al., 2005) and more planets on highly elliptical orbits at moderate separations from their stars (Dawson and Murray-Clay, 2013). These results support the core accretion model of planet formation, in which disks hosting more solid material more easily form solid cores massive enough to accrete giant envelopes. However, scientists do not yet understand the range of environments in which gas giants can form (must it be in a cold, ice-rich location?) or how they form (do all giant planets first begin as solid cores of a specified mass, and then accrete gas?). Importantly, most of the mass of gas giants is contained in their gas envelopes, meaning that their formation time scale is closely tied to that of disk gas dissipation.

The location and time scale of the formation of giant planets, in turn, can have an enormous impact on the prospects for forming small planets in the same system. The relationship between the inner and the outer parts of planetary systems constrains models of formation, with implications for migration histories and compositions. For example, no consensus yet exists about whether the super-Earths with orbital periods less than one year, that are known to orbit perhaps a third of stars, are icy bodies formed in outer disks that then migrate to their present locations or if they form in situ from primarily rocky material.

The desire to understand planet formation cannot be satisfied by finding only the small planets close to their stars (as discussed below, neither can the desire to understand habitability). Only by first measuring the full architecture of planetary systems can the correlations between architectures, compositions, and stellar properties be established to ultimately lead to an understanding of planet formation. For example, do stars with high ratios of silicon to iron form more solid material, and are they ultimately more efficient at building the cores of large planets? Do less massive stars form less massive planets, revealing that initial disk mass is an important controlling parameter? Do systems hosting close-in super-Earths typically also contain distant gas giants, suggesting that they are products of disks with large masses in solids? And alternatively, are super-Earths anti-correlated with gas giants, suggesting that they form when most disk solids are able to migrate into the inner system? Are multiple cold planets not close to resonance while multiple warm planets are, suggesting that migration distances in disks are larger in inner than outer disks? Are stellar binaries of certain mass ratios and separations incapable of forming planetary systems? Or is planet formation so inevitable that it is largely insensitive to binarity?

The chemistry of planets is inherited from the disks from which they form. The Solar System bodies provide substantial clues to expectations about disk inheritance, including more volatile rich material in the outer regions at large distances from the Sun, substantial mixing in the early solar nebula that leads to high temperature condensates in comets and similar organics in both comets and asteroids (Keller et al., 2008), and evidence for giant impacts late in the formation process. While exoplanetary systems can have vastly different architectures than the Solar System, these chemical segregation and mixing processes depend on physics that should operate in all disks. Merely knowing of the existence of planets (and their bulk properties) is not sufficient: a statistical sample of atmospheric compositions at a range of orbital distances is also required, to test the link between planet composition, location of formation, and migration distance.

Major facilities to study planetary atmospheres should ensure that instrument design and survey design allow for characterization of a diverse planet population. Eventually, the goal is for population synthesis models to incorporate accurate disk physics and predict the correct distribution of planets in a statistical sense. With limited spectral coverage, interpretation of planetary atmospheric compositions will likely be ambiguous. Planet formation studies can help resolve this ambiguity, but only if enough empirical information is provided across a range of systems.

> **Finding:** Current knowledge of the demographics and characteristics of planets and their systems is substantially incomplete. Advancing an understanding of the formation and evolution of planets requires two surveys: First, it requires a survey for planets where the census is most incomplete, which includes the parameter space occupied by most planets of the Solar System. Second, it requires the characterization of the atmospheres and bulk compositions of planets spanning a broad range of masses and orbits.

Toward a More Complete Statistical Census of Exoplanets

Determining the demographics of exoplanets is challenging for two reasons: First, knowing how the planet population varies as a function of a number of parameters, such as stellar mass, stellar metallicity, planet mass, and orbital period, is needed; and exploring each new dependency is resource intensive. Second, different detection methods are sensitive to different kinds of stars, planets, and orbital periods. Exacerbating the challenge, the ranges of sensitivities often do not overlap, requiring extrapolation to connect the populations inferred by different methods (Figure 3.1).

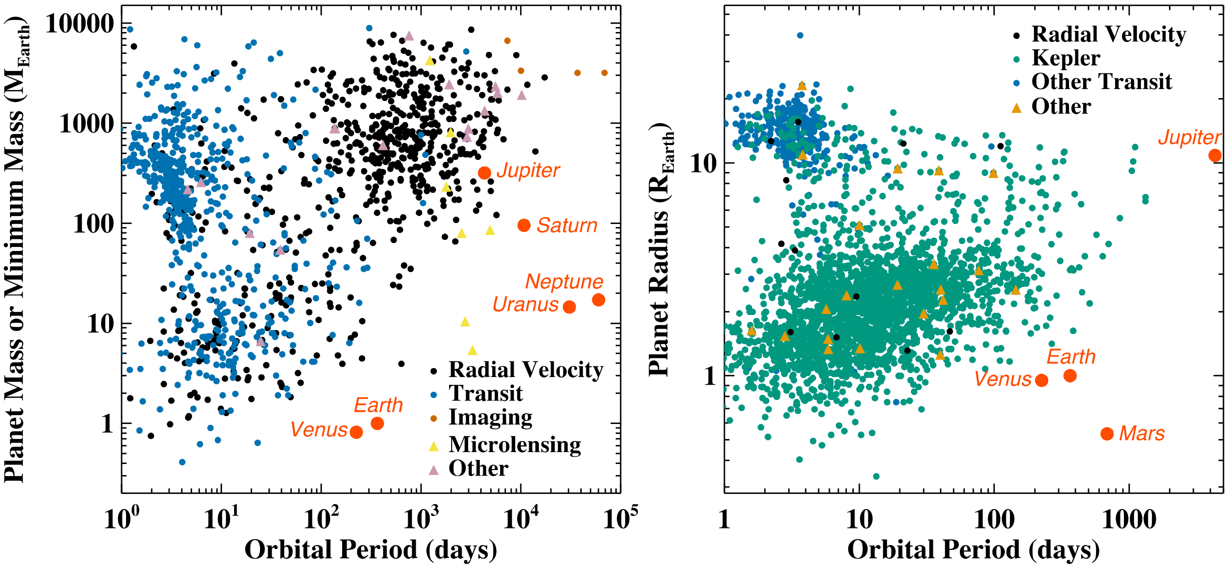

FIGURE 3.1 The distribution of known exoplanets as a function of their orbital periods and mass (left panel) and radius (right panel). The method of discovery is shown in the legend by color and symbol. Most planets discovered by radial velocity do not transit, so they do not have measured radii. Most planets discovered by transit do not have measured masses. The exoplanet census does not yet include the full radius and mass range covered by the Solar System planets. SOURCE: A. Weinberger, using data from the NASA Exoplanet Archive, a service of the NASA Exoplanet Science Institute.[1]

As described in Chapter 2, the radial velocity and transit methods have provided a statistical census of the planet population of close-in planets with separations of less than roughly one AU and masses or radii greater than that of Earth, and imaging has provided a first look at the population of young (and hence luminous) massive worlds far from their stars. However, other than the several dozen precious detections from microlensing, knowledge of the population of mature planets on long orbits is woefully incomplete. This leaves researchers unable to probe planets as a function of where ices such as water condense (snow lines), although these transitions appear important in the Solar System and in protoplanetary disks. Furthermore, the population of known planetary systems in the parameter space of planets mass (or radius) and semimajor axis (or period) is nearly completely disjoint from the parameter space covered by the planets in the Solar System. As discussed in Chapter 2, the detection methods that are best positioned to contribute to improving a statistical census of planets, particularly analogues of the planets in the Solar System, are astrometry, microlensing, and direct imaging.

The Gaia astrometric mission (Perryman et al., 2011) is currently operating and, by the end of its mission, it will have an astrometric accuracy sufficient to discover roughly 20,000 planets with masses at

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[1] See https://exoplanetarchive.ipac.caltech.edu/.

least as great as Jupiter, and in orbital periods of less than 6 years (Perryman et al., 2014). The region of parameter space probed by Gaia will overlap significantly with that of radial velocity surveys, but Gaia will inform us of masses and the relative inclinations of the orbits in multiplanet systems. Furthermore, Gaia will be sensitive to planets orbiting stars more massive (and, thus, at different evolutionary states) than those probed by radial velocity surveys. And, because Gaia's yield of planets is substantially larger than any other previous exoplanet survey, it will be uniquely sensitive to rare systems, which often provide deep insight into the processes of planet formation and evolution (e.g., HD 80606; Naef et al., 2001).

Nonetheless, Gaia will not, in general, provide access to the population of planets that are either lower mass or more distant than Jupiter, particularly for Sun-like stars (Casertano et al., 2008). Therefore, Gaia will not probe the majority of the parameter space that is spanned by the Solar System planets with the exception of Jupiter analogues, or indeed a region of parameter that is has not already been surveyed by radial velocity surveys. An understanding of planet formation is critically informed by the existence of planets with masses less than, and separations greater than, Jupiter.

A Space-Based Microlensing Survey

As described in Chapter 4, in the section "Expanding the Statistical Census of Exoplanets," the essential survey that will largely complete the statistical census of exoplanets is the WFIRST microlensing survey. Combining the findings of WFIRST with previous transit and radial velocity surveys will

- Measure the frequency of planets with masses greater than Earth at all relevant separations;
- Measure the frequency of planets with masses as low as that of Mars out to several AU;
- Be sensitive to bodies with masses as low as several times the lunar mass, including objects orbiting Earth-mass planets;
- Determine if the frequency of planets in the galactic bulge is significantly different from that in the neighborhood of the Sun; and
- Measure the mass function of free-floating planetary mass objects, whose occurrence rate and mass function likely provide a strong indicator of the dominant formation processes of exoplanetary systems.

A limitation of WFIRST microlensing is that it is typically sensitive to only one planet in each system (for some events, it will detect multiple planets, but not all planets). The committee notes the complementarity here with the direct imaging method, which is discussed later. Direct imaging can detect planets over a broad range of separations, and thereby tie the population of outer planets (i.e., analogues of Jupiter and Saturn) with the presence of any worlds in the habitable zone. Given that the existence of a giant planet may or may not affect the habitability of the terrestrial world, this feature of direct imaging surveys is quite important. Direct imaging facilities will deliver detailed characterization of a comparatively smaller number of planetary systems, which will provide important constraints on the physics of planetary atmospheres and interiors, and on the architectures of planetary systems, including the frequency with which terrestrial planets have outer giant planets.

What Gaps Will Remain in the Planetary Census?

Although the execution of Gaia and WFIRST will greatly expand the statistical census of exoplanets, gaps in knowledge of the demographics of exoplanets in certain regions of parameters space will nevertheless remain.

- Protoplanetary and debris disk observations probe dust grains up to a mm in size, whereas the exoplanet detection techniques are sensitive to planets with masses greater than that of roughly the moon. This is a 36 order of magnitude gap between observations of protoplanetary disks and mature planetary systems, thus there exists a very large gap in the mass and radius of solid bodies.
- Understanding of the demographics of planets in binary stars is incomplete. Many planets orbiting one member of a wide binary have been discovered, and a handful of circumbinary planets, but the physical processes that govern the formation of planets in these systems remains poorly understood.
- The demographics of planets orbiting young stars would be exceptionally valuable. This could constrain the initial conditions of planet formation after gas dispersal, thereby potentially cleanly separating the effects of gas dynamics from N-body dynamics. The activity of young stars makes planet detection difficult, except for the method of direct imaging (Pollack et al., 2006). If calibrated by future observations of disks and planets in the same systems, features in the dust distributions of protoplanetary and young debris disks may provide an additional window into this population.
- The dynamical characteristics of its resident planetesimals and satellites have greatly constrained models of the Solar System's formation. For example, resonance structures in the asteroid and Kuiper belts reveal that the Solar System's giant planets migrated from their formation locations. The dust produced by planetesimal belts in extrasolar systems can be probed with direct imaging instruments. However, satellites of exoplanets are difficult to detect, and none has yet been confirmed. In principle, one can detect satellites via timing variations or flux anomalies for transiting planets (Kipping, 2009). Microlensing is also sensitive to large-mass moons, but the sensitivity is poor for typical planet-moon separations (Bennett and Rhie, 2002).

Characterizing the Atmospheres and Interiors of a Diversity of Exoplanets

The study of exoplanet atmospheres and interiors presents a complementary way to advance knowledge of planet formation and evolution, and provides a unique window into the physics and chemistry of planetary environments. Some of the pressing questions in planet formation and evolution are outlined below, with the associated physics and chemistry of their atmospheres. The diversity of exoplanets presents both a challenge and opportunity for characterizing the atmospheres and interiors of these objects. Diversity presents a challenge, because it means that individual planets are not fully representative of a broad class of objects, and large samples are likely needed to reveal the properties of distinct populations. On the other hand, diversity is an opportunity: by looking at similar objects in different regimes, and in regimes not represented by the Solar System planets, the effects of the different physical processes can, hopefully, be untangled.

Giant Planets

Giant exoplanets present the opportunity to understand the growth of planets in gas-rich protoplanetary disks. The core nucleated accretion model for giant planet formation has been largely validated for planets that are found within 5 AU of their stars. Nevertheless, key questions remain, including the role of the core, the location of formation, and the effect of migration.

The core nucleated accretion model posits that the formation of giant planets is seeded by the growth of a solid core that reaches a critical mass that is sufficient to initiate runaway accretion of nebular gas (Pollack et al., 1996). The classic value for the critical core mass is 10 M_E, but can vary substantially depending on the details (Rafikov, 2006). Therefore, it would be extremely valuable to know the core masses of giant planets. However, measurements of the absolute core masses of giant planets is a notoriously difficult problem even for the Solar System giants, due to uncertainties in equations of state and model degeneracies (Fortney and Nettelmann, 2010).

The challenge of determining core masses can be somewhat overcome for giant exoplanets by focusing instead on relative rather than absolute values. Under the same model and equation of state assumptions, the relative amount of heavy elements in the interiors of exoplanets can be inferred from knowledge of masses and radii (Miller and Fortney, 2011). As described in Chapter 2, initial studies indicate that planetary heavy element abundances are correlated with the metallicities of the stellar hosts (Thorngren et al., 2016). These studies should be expanded to explore how the bulk heavy element abundance of giant planets changes with planet mass, orbital distance, and host star mass and composition. This requires precise measurements of the masses and radii of a sample of planets that are less irradiated than the ones studied to date.

As described above, the envelopes of giant planets are thought to form by runaway accretion of nebular gas. Therefore the atmospheric compositions of giant planets should be broadly similar to those of their host stars. On the other hand, the core accretion model is based on the assumption that giant planets form in a region of the disk that is rich in solid planetesimals. These planetesimals sequester heavy elements out of the gas, with their composition depending on the temperature and dynamics of the disk, and the gas, ion, and surface chemistry. Some of the planetesimals will dissolve in the atmosphere and return heavy elements to the gas. Migration can also lead to giant planets feeding from different parts of the disk. Thus, the ways in which the atmospheric compositions of giant planets differ from their host stars can be used to constrain the chemistry and surface density of solids, the migration pathway, and the overall formation mechanism (e.g., Oberg, Murray-Clay, and Bergin, 2011; Mordasini et al., 2016).

The atmospheric compositions of the solar-system giant planets have been used for decades as a tracer of their origins. Figure 3.2 summarizes what is known from a combination of Earth-based observations, orbiters and flybys, and in situ measurements (Atreya et al., 2016). Despite the significant investment in studying these planets, it is surprising how little is known about their elemental makeup. There is good reason for this, which is that the Solar System giants are relatively cold and thus most key chemical species have condensed out of their observable atmospheres. Jupiter is the exception solely because of the in situ measurements by the Galileo entry probe (Owen et al., 1999).

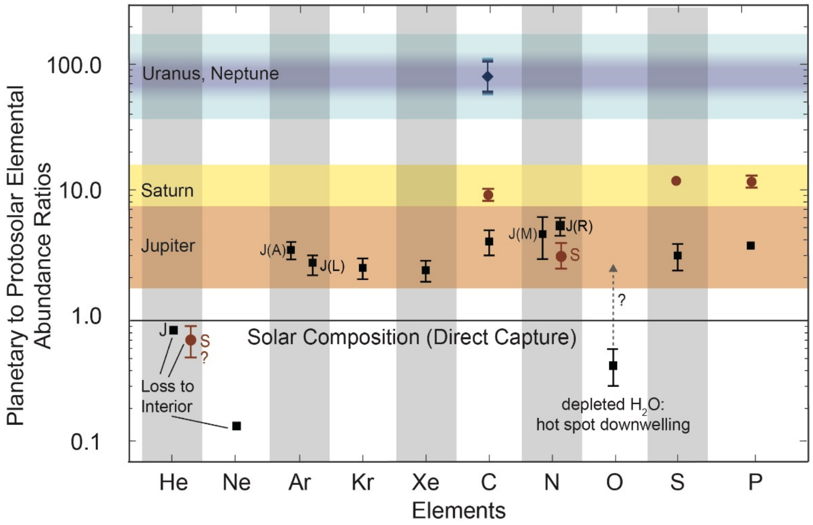

FIGURE 3.2 Elemental abundances relative to the original nebular abundances for the giant planets of the Solar System. The overall enhancement of metals in the atmospheres supports the core accretion model, while the relative elemental abundances (e.g., C/O) constrain the detailed history of each planet. SOURCE: Atreya et al. (2016).

Exoplanets offer several important advantages in the study of giant planet atmospheric compositions. First, the atmospheres of hot giant exoplanets can be studied, and for these planets many of the sought-after chemical species are in the gas phase and observable. A much wider range of elemental abundances can be measured for exoplanets than for the Solar System giants. It should be possible to determine the carbon, nitrogen, and oxygen abundances, which is important because these elements make up the bulk of the solid planetesimals that are crucial for giant planet formation.

Figure 3.3 shows what is known about the atmospheric metallicities of the solar-system giant planets, and exoplanets. In the Solar System, the methane abundances increase toward smaller planet masses, consistent with the expectation from the core accretion model. Water abundances for transiting planets are just now being measured and added to this diagram (e.g., Kreidberg et al., 2014). Upcoming work using both transit and direct imaging techniques should expand these studies to achieve a more complete assessment of metallicity (by measuring more chemical species), and to determine the elemental abundance ratios, such as C/O.

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FIGURE 3.3 Increase in atmospheric metallicity (relative to that of the host star) as a function of planet mass. In the Solar System, methane is the proxy, while for exoplanets it is water. The black dashed line shows a model fit to the Solar System planets, with an enforced minimum value of unity. Exoplanets can fill in this diagram with tens or even hundreds of planets. These studies can be expanded straightforwardly to additional parameters like semimajor axis and stellar mass. SOURCE: Mansfield et al. (2018).

Another advantage of exoplanets is the opportunity to study a much larger sample than that afforded by the Solar System. This is important because planet formation represents the stochastic outcome of a variety of physical processes (resulting in, for example, a predicted spread in the planetary mass-metallicity relationship; Fortney et al., 2013). Furthermore, the population of exoplanets affords the possibility to learn how atmospheric composition depends upon orbital semimajor axis and host star mass. Characterization of many planets will be needed to reveal even the simplest trends that are expected from models.

Formation by gravitational instability could play a role in the colder, outer regions of planetary systems. Young planets with ages <100 Myr that are still evolving will retain the imprint of their initial entropy in the form of their radii and temperatures; giant planets formed by disk instability should have higher entropy and thus larger radii and temperatures than similar planets formed by core accretion (Spiegel and Burrows, 2012). Determining the temperatures and surface gravities (a proxy for radius) for a large sample of distant, young, self-luminous planets will constrain the roles of the core accretion and disk instability mechanisms. Exploration via direct imaging of the boundary between wide-separation giant planets and brown dwarf binary companions will also inform whether a population of companions formed through gravitational instability exists (Kratter, Murray-Clay, and Youdin, 2010).

Straddling the Gap

The surprising discovery of an abundance of planets with masses and sizes between that of Earth and Neptune allows us to investigate the crossover regime between rocky terrestrial planets and gas-rich giants. It was previously thought that cores of 10 M_E were necessary to initiate runaway gas accretion (e.g., Ida and Lin, 2004), but mass-radius measurements indicating low bulk densities and implying hydrogen-rich envelopes for planets below this mass have cast doubt on this idea (see Chapter 2). A range of theories for forming low-density super-Earths and mini-Neptunes now exist. Yet the relative importance of gas accretion onto smaller cores, degassing of volatiles, and accretion of ice-rich material from large orbital separations in sculpting the population of low-mass low-density exoplanets remains to be determined. Atmospheric observations will play a pivotal role in addressing these ideas.

Few observations of the atmospheres of sub-Neptune size exoplanets currently exist. Of the ones that do, most are featureless transmission spectra resulting from aerosol-dominated atmospheres (e.g., Kreidberg et al., 2014; Knutson et al., 2014). However, not all planets are dominated by aerosols (e.g., the recent detection of water absorption in GJ3470; Tsiaras et al., 2018), thus observations of more planets should reveal the desired gas phase compositions. Furthermore, broader wavelength and higher spectral resolution transmission spectroscopy observations, and thermal emission spectroscopy observations have the potential to see through obscuring aerosols. These observations will allow us to directly probe the composition of planets in the transition regime between giants and terrestrials.

The shift from gas-rich to rocky planets is apparent in the bimodal radius distribution of exoplanets discovered by Kepler (Chapter 2). While this transition is now well defined in radius, it will be illuminating to study it in terms of density and atmospheric composition. By exploring the mass-radius relation for planets smaller than Neptune and their atmospheric compositions, the true range of outcomes for planet formation and evolution can be studied in an intermediate size range that is not represented in the Solar System. Outstanding questions that researchers hope to answer for these planets include the following:

- Over what range of masses, insolation, and formation time scale are planets able to retain hydrogen-rich atmospheres?
- What are the relative roles of outgassing, accretion, and atmospheric escape in forming the atmospheres of sub-Neptune size exoplanets?
- Do intermediate size exoplanets come only in the form of mini-Neptunes and super-Earths, or do water-dominated hydrogen-poor worlds also exist?

Rocky Planets

The secondary outgassed atmospheres of terrestrial exoplanets are expected to be far more compositionally diverse than those of the larger gas giants. The atmospheric composition of a terrestrial exoplanet results from complex processes related to the dynamical history of the planet, its accretion history (both of solids and gas), its thermal history, and its interactions with its host star via high-energy photons and stellar winds.

The required observations of terrestrial exoplanet atmospheres do not yet exist due to the tiny size of their atmospheric signatures against the background of their host stars. Even the James Webb Space Telescope (JWST) will be hard pressed to make meaningful observations of temperate terrestrial planetary atmospheres, except for in the few most optimal cases of planets orbiting mid-to-late M dwarfs. As discussed in Chapter 4, in the section "The Case for Imaging," flying a large space-based direct imaging mission will be the most productive strategy for performing atmospheric characterization of a large number of terrestrial planets over a range of orbital separations.

Precise measurements of the masses and radii of terrestrial planets will play an essential role in exploring their interior structures. The ratio of the iron core to the rocky mantle can be constrained for terrestrial planets (e.g., Zeng and Sasselov, 2013). The near-term study of the diversity of terrestrial exoplanets will provide the vital context for future studies of habitable exoplanets and the search for life beyond the Solar System.

Physics and Chemistry of Planetary Environments

Atmospheres are the principal window into the physical processes that shape planetary environments. Atmospheres govern planetary climate by mediating the balance between stellar irradiation, reradiated flux, and a planet's intrinsic luminosity. Heat transport moves energy vertically and horizontally, but strong temperature gradients can persist in altitude, longitude, and latitude. Testing theories of heat transport requires determining how the albedos, bolometric luminosities, thermal structures, and atmospheric circulation vary with planetary irradiation, surface gravity, and rotation rate. Current observations focused mostly on transiting hot Jupiters have raised the question of how temperature inversions arise on highly irradiated planets and how such planets transport energy from their permanent daysides to their permanent nightsides (e.g., Parmentier et al., 2018; Parmentier and Crossfield, 2017). These preliminary results demonstrate the need for broad wavelength coverage to accurately determine bolometric luminosities and albedos, spectroscopic mapping to reveal the full planetary context, and more advanced models that incorporate a wider range of physics and chemistry.

Chemical gradients often follow temperature gradients, with condensation/evaporation, dissociation/recombination, and oxidation/reduction states varying. Furthermore, nonequilibrium effects like photochemistry and quenching can alter the composition as well. For example, carbon chemistry is a sensitive probe of atmospheric conditions. For hydrogen-rich atmospheres CH_4 is expected to be the dominant carbon-bearing molecule at low temperatures and CO at high temperatures. However, CH_4 is also readily photolyzed, so it may be absent from atmospheres in which it would otherwise be expected from equilibrium chemistry considerations. For the oxidizing atmospheres of terrestrial exoplanets, CO_2 is expected to become the primary carbon-bearing species. For nitrogen, a similar balance occurs between N_2 and NH_3, the latter of which is also photochemically sensitive and may be converted to either N_2 or HCN. Ultimately, measuring the abundances of a wide range of chemical species for a wide range of planets will be needed to fully explore the various chemical pathways in exoplanet atmospheres.

The formation of aerosols both by equilibrium and nonequilibrium processes is an especially pernicious problem in planetary atmosphere chemistry. Through their opacities, aerosols impact the observability of gas phase chemical species and influence planetary energy budgets. Condensation more generally can also sequester key elements out of view as described above for the giant planets of the Solar System.

While problematic from the standpoint of spectroscopic observability, the presence of aerosols are also signposts of the physical and chemical processes occurring in planetary atmospheres. For example, photochemical hazes indicate disequilibrium chemistry and photolysis processes occurring in the upper atmospheres. For condensate clouds, diagnosing their composition can be used to probe both the chemical makeup and the thermal structure of an atmosphere. Aerosols also serve as tracer particles to determine planetary rotation periods and dynamics (e.g., Apai et al., 2017).

At the lower boundary, atmospheres are coupled to the planetary interior, including through outgassing and drawdown processes at the surface interface for terrestrial planets. Terrestrial planets can also be impacted by biological activity. Therefore, atmospheric compositions are an important diagnostic of planetary geophysics, habitability, and life (see the following section).

> **Finding:** Characterizing the masses, radii, and atmospheres of a large number of exoplanets with a range of physical and orbital parameters for a diverse set of parent stars will yield fundamentally new insights into the formation and evolution of planets and the physics and chemistry of planetary environments.

THE SEARCH FOR LIFE

Recent advances toward understanding the context for biosignatures, as well as the factors that make a planet hospitable to life, underpin the second major goal of exoplanet science:

> **Goal 2:** 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.

To achieve this goal and support the search for life in the galaxy, the following two areas of interdisciplinary research need to be developed:

- A multiparameter habitability assessment for target selection; and
- A comprehensive framework for biosignature assessment.

In parallel with these theoretical underpinnings, a sequence of observational milestones need to be achieved to

- Identify and rank exoplanet targets;
- Characterize the environment, including the atmosphere, surface, and interior of the planet, and the spectrum and variability of the star; and
- Search for life in the context of the planetary and stellar environment.

The habitable zone (Kasting et al., 1993; Kopparapu et al., 2013) has been a practical but simplistic way to assess exoplanet habitability, depending upon only two readily observable characteristics: the planet-star distance, and the type of star. Going forward, a more comprehensive multiparameter habitability assessment, combining laboratory and theoretical computer modeling with constraints from observations, will be needed to rank exoplanets for observational searches for biosignatures. Similarly, a framework for biosignature assessment based on laboratory and field measurements, as well as theoretical modeling to predict key observables needed to discriminate between abiotic and biological sources, will allow researchers to interpret putative biosignatures in the context of their environment, and thereby increase the credibility of their interpretation. As part of this framework, novel biosignatures need to be considered and abiotic processes that could mimic the signs of life need to be identified.

These precursor studies will both inform the measurement requirements for future instruments and will be necessary to interpret the resulting data. In the near term, the search for habitable environments and signs of life will focus on transiting M dwarf planets (see below and the section "Opportunities to Characterize Planets Through Transits," in Chapter 4). In the longer term, direct imaging facilities will search for indicators of habitability and life on planets orbiting stars closer in mass to the Sun (see below and the section "The Case for Imaging," in Chapter 4). These studies will be complemented by statistical surveys on larger samples of terrestrial planets that provide information on planet demographics and bulk properties for terrestrial planets both interior to and outside the habitable zone. Additionally, the ability to confidently identify habitable planets and life will rely on the expertise of several disciplines outside of traditional astronomy (see below and the sections "Astrobiology" and "Mechanisms to Achieve Interdisciplinarity," in Chapter 4).

Understanding the Factors That Affect Habitability and How to Measure Them

An improved understanding of the planetary-system-wide impacts on habitability requires research that explores exoplanets as systems, including the exchange between the interior and atmosphere, the interaction between the planet and its parent star, and the planetary system architecture (see Figure 3.4). The following processes, including those occurring on Solar System planets, should be studied to better understand how a planet can acquire and maintain habitability.

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FIGURE 3.4 Factors affecting habitability. This diagram shows known planetary, stellar, and planetary system properties that may impact a planet's ability to support a surface liquid water ocean. Additional factors that can be determined or constrained for a given habitable zone candidate will improve assessment of potential habitability. Font color denotes characteristics that could be observed directly with sufficiently powerful telescopes (blue), those that require modeling interpretation, possibly constrained by observations (green), and the properties or processes that are accessible primarily through theoretical modeling (orange). SOURCE: Meadows and Barnes (2018).

Planetary Properties

The exoplanet science community needs to expand its knowledge of intrinsic planetary properties that make habitability more likely and identify observational discriminants for those properties (Figure 3.4). For example, as outlined in Chapter 2, in the section "The Search for Life on Exoplanets," a habitable planet is most likely terrestrial with a solid surface that supports a liquid water ocean formed from initial volatile content, and with orbital parameters that allow a habitable surface temperature. It must also have lost most or all of its primary H_2-dominated atmosphere (Owen and Mohanty, 2016; Pierrehumbert and Gaidos, 2011) and resisted the loss of its ocean and secondary atmosphere (Meadows and Barnes, 2018).

The presence of a planetary atmosphere strongly impacts habitability by providing the surface pressure required to maintain a surface liquid ocean against escape processes (Hunten, 1973; Wordsworth and Pierrehumbert, 2014; Garcia-Sage et al., 2017). The composition of that atmosphere—including the noncondensable bulk composition, greenhouse gases, clouds and hazes—modifies the atmospheric thermal structure and could provide a habitable surface temperature (Rauer et al., 2011). Atmospheric gases and aerosols help shield the planetary surface from UV flux (Segura et al., 2003, 2005; Rugheimer et al., 2015, 2017; Arney et al., 2016). Both atmospheric pressure and composition play a role in buffering day-night and seasonal temperature differences, including reducing the probability of atmospheric collapse via freeze-out on the nightside of synchronously rotating planets (Joshii and Haberle, 2007; Turbet et al., 2016, 2017). The presence of an ocean (Hu and Yang, 2014) can also buffer day-night temperature differences and help a synchronously rotating planet avoid atmospheric collapse.

Since terrestrial planets are more likely to support a surface ocean, a critical area of future research in planetary habitability will be the loss, maintenance and replenishment of secondary terrestrial atmospheres. Moreover, the current understanding of the evolution of terrestrial exoplanets, with a diversity of compositions and host star environments, will need to improve. A key component will be understanding degassing for terrestrial planets of different compositions, including potentially more volatile-rich migrated planets that may be found orbiting M dwarfs, both inside and far from the nominal habitable zone (Gillon et al., 2017; Luger et al., 2017b; Grimm et al., 2018; Berta-Thompson et al., 2015; Dittmann et al., 2017; Meadows and Barnes, 2018).

Stellar Properties

The host star's composition, gravity, and irradiation can strongly influence the formation, and orbital, interior, and atmospheric evolution of all classes of planets. For habitable zone terrestrials, however, the host star's characteristics can also strongly impact whether or not the planet is able to acquire and maintain also have a strong impact on the planet's environment and habitability. In particular, and the star's evolution in luminosity (Baraffe et al., 1998) drives strong climate change and may result in atmospheric or ocean loss (Ribas et al., 2016; Barnes et al., 2018; Dong et al., 2016). The stellar spectrum and activity also influence atmospheric escape and climate, and photochemically modify the atmospheric composition (Meadows and Barnes, 2018). Indeed, the need to understand the illuminating star is paramount for understanding all irradiated planets, whether or not they might be habitable.

For photochemical models to predict and interpret atmospheric conditions, including planetary surface UV flux, knowledge of the high-energy stellar fluxes, spectral slopes and variability are needed. For habitable zone terrestrial planets, especially those in close-in orbits around M dwarfs, the high-energy photon and proton flux is even more critical to understand (Segura et al., 2005; Segura et al., 2010; Rugheimer et al., 2015; Tilley et al., 2018). It is therefore essential to obtain stellar UV spectroscopy on different time scales for stars of different stellar type and ages, to characterize stellar UV fluxes and variability. This is especially needed in the near-term to prepare for and interpret atmospheric observations of M dwarf exoplanets with JWST (e.g., for the TRAPPIST-1 system and GJ1132b;

Lincowski et al., 2018) and large ground-based telescopes (e.g., Proxima Centauri b; Lovis et al., 2017; Snellen et al., 2015).

Stellar activity levels and UV slopes can be quantified with broadband photometry obtained from space-based observatories such as the Galaxy Evolution Explorer (GALEX) or the Hubble Space Telescope (HST), or via CubeSat missions such as the Star-Planet Activity Research CubeSat (SPARCS; Shkolnik et al., 2018) or the Colorado Ultraviolet Transit Experiment (CUTE; France et al., 2018). Additionally, visible light proxies for UV emission can be obtained from ground-based telescopes. However, wavelength-dependent spectral information on flares and the stellar extreme-ultraviolet (XUV) to near-ultraviolet (NUV) region can be done currently only with UV spectroscopy from HST, which is nearing the end of its mission lifetime. It is critically important to gather UV information on main sequence stars that may host exoplanets, before this capability is lost. Additional ground-based work characterizing stellar variability and activity (especially for M stars), and enhanced communication with stellar astrophysicists would advance the field.

Planetary System Architecture and Evolution

Other components of a planetary system, such as Jovian planets, asteroid and Kuiper belts, and nearby sibling planets, can also affect the potential habitability of a habitable zone planet and provide clues to its formation and evolution history (Raymond et al., 2008; O'Brien et al., 2014; Meadows and Barnes, 2018). In particular, the masses, orbits, and migration history of Jovian planets should be characterized to the extent possible, as they can affect volatile delivery to forming terrestrial planets, and eccentric Jovians could result in the formation of water-poor terrestrials (Raymond et al., 2004; Raymond et al., 2007; Lissauer, 2007; Meadows and Barnes, 2018). Nearby sibling planets can also modify orbital parameters, including eccentricity and obliquity. Belts of minor planets analogous to the asteroid and Kuiper belts (and detectable as infrared excesses) serve as a reservoir for water-rich bodies and impactors, and the disk's dust distribution can reveal the gravitational signature of unseen planets (Chambers, 2001; Raymond et al., 2011). Exomoons also influence habitability by damping large obliquity oscillations, but remain challenging to detect (Meadows and Barnes, 2018).

Star-Planet-Planetary System Interactions and Habitability

While the characteristics of planet, star, and planetary system described above can increase or decrease the probability that a planet is habitable, they do so via interactions between the planet, its host star, and its planetary system (Meadows and Barnes, 2018). An improved understanding of these interactions is needed to fully understand the impact on a planet's environment and predict observable consequences. Some of the key interactions affecting planetary habitability are described below.

Stellar Composition, Planet Formation, and the Delivery of Volatiles

Planet formation, migration, and the delivery of volatiles are key processes that determine the composition and structure of a planet, and whether or not it can be habitable. Importantly, reliable planet formation models can provide essential constraints on planetary properties that are difficult or impossible to observe directly. If models or observations suggest that a planet is more likely to have formed with a very low volatile abundance, then it has less chance of being habitable. For example, while initial modeling of the formation of M-dwarf terrestrial planets suggested that they might form with little water (Raymond et al., 2007; Lissauer, 2007), recent measurements of the density of Earth-size planets orbiting the M8V TRAPPIST-1 star suggest that they are instead volatile-rich (Grimm et al., 2018). This may be due to a history of forming in a more volatile-rich birth orbit and then migrating inward, which is suggested by their resonant chain of orbits (Luger et al., 2017). An improved knowledge of stellar compositions is also required to constrain planetary evolution models and for habitability assessment (Young et al., 2018). Measurements of stellar composition can provide insight into the nature of the planets themselves, and can be combined with the planet's mass and radius, and planet formation and differentiation models to provide clues to the planet's composition and interior structure (Dorn et al., 2015; Unterborn et al., 2015; Meadows and Barnes, 2018).

Star-Planet and Planet-Planet Orbital and Tidal Interactions

Planets that orbit close to their parent stars ($a < 0.1$ AU) are affected by tides, and this may include planets in the habitable zones of smaller stars. In addition to tidal locking (Dole, 1964; Barnes et al., 2017), which can result in synchronous rotation, tides may impact habitability via orbital circularization and migration (Rasio et al., 1996; Jackson et al., 2008), obliquity erosion (Goldreich et al., 1966; Heller et al., 2011), and tidal heating (Jackson et al., 2008; Barnes et al., 2013). Synchronous rotation may, in turn, increase the chance of atmospheric collapse (Joshii et al., 2003; Turbet et al., 2016); but it also can be avoided if a nonzero eccentricity or obliquity can be maintained via perturbation by another planet (Barnes et al., 2010). Planets in noncircular orbits can be tidally heated, changing their internal properties and outgassing rates. Consequently, any constraints on a planet's orbital and rotation state, and its age, will provide key clues to processes that will impact habitability. These constraints may eventually be obtained via time-dependent multiwavelength mapping using direct imagers to constrain planetary rotation, and from improved stellar ages.

Star-Planet Radiative Interactions and Evolution

Venus, Earth, and Mars exhibit secondary atmospheres that are likely composed of fractionated remnants of the primordial atmospheres, augmented by outgassed volatiles from the planetary interior and volatile delivery from other bodies in the system (Pepin, 2006; Meadows and Barnes, 2018). If the secondary atmosphere is lost at a rate that outstrips replenishment, then the atmosphere would be lost, and surface habitability would be precluded. To assess the potential for exoplanet habitability, especially for planets orbiting M dwarfs, it is critical that interdisciplinary studies are undertaken that explore the interactions of stellar luminosity, activity evolution and the stellar wind, with planetary atmospheres, interior/atmosphere exchange, and magnetic fields.

As described by Meadows and Barnes (2018), atmospheric escape can be driven by radiation from the star, solar wind interactions, and impact erosion (Ahrens, 1993; Quintana et al., 2016). Comparison of Solar System bodies with and without atmospheres, along with exoplanets, suggests that there is an empirically derived "cosmic shoreline" as a function of planetary insolation and escape velocity that appears to be governed by thermal escape processes, and which divides planets with and without atmospheres (see Figure 3.5; Zahnle and Catling, 2017). Larger-mass planets will better resist atmospheric loss due to EUV/XUV and impacts, whereas planets with magnetic fields can deflect losses due to the solar wind (Meadows and Barnes, 2018). Because of their extended super-luminous pre-main-sequence phase and high activity levels, M-dwarf planets may be particularly vulnerable to atmospheric and ocean loss via hydrodynamic escape processes (Lammer et al., 2008; Luger and Barnes, 2015; Meadows et al., 2018; Barnes et al., 2018; Meadows and Barnes, 2018). Observations and models that can confirm the presence of an atmosphere, as may be possible with transmission spectroscopy or direct imaging, or identify the factors most likely to contribute to atmospheric loss (such as stellar XUV flux and evolution) will help to rank exoplanet targets for study and biosignature searches.

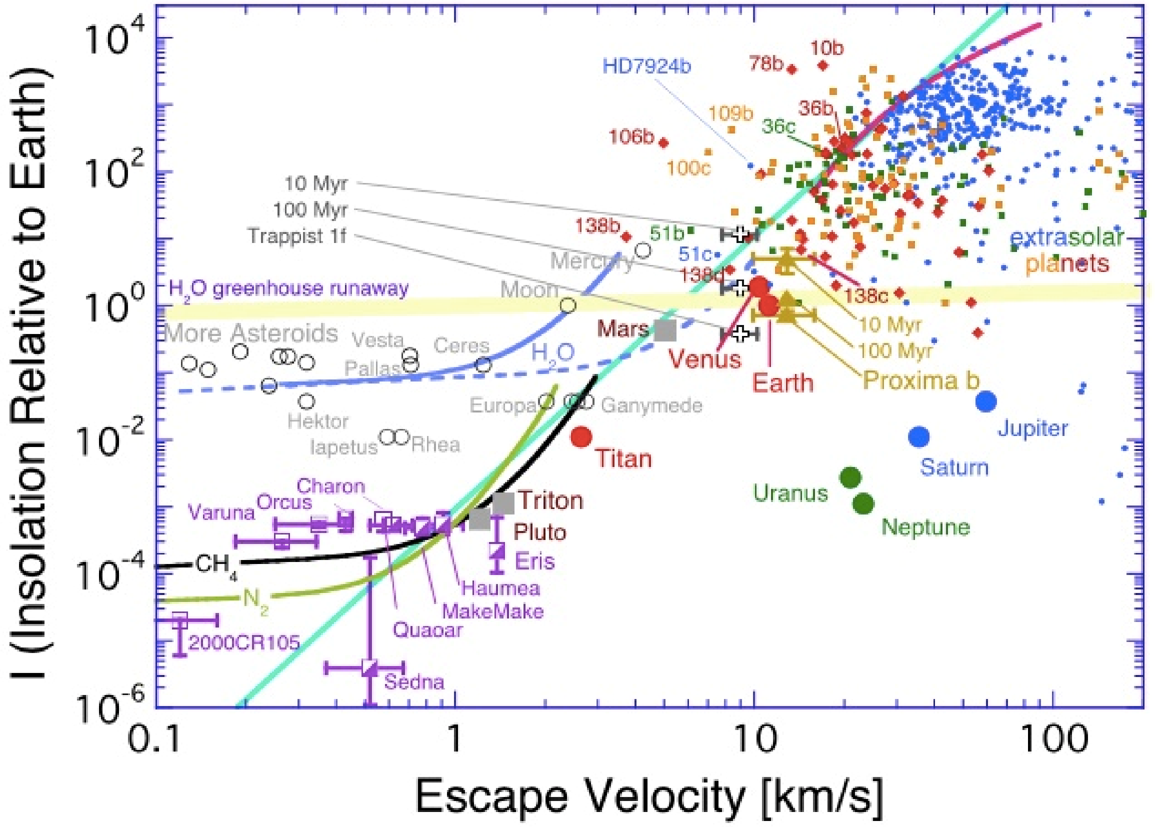

FIGURE 3.5 The cosmic shoreline. This figure depicts a plot of planetary stellar insolation relative to Earth's as a function of escape velocity. Solid symbols denote those objects with atmospheres, and open symbols show bodies with no atmosphere. Solar System bodies are named, and extrasolar planets with known masses and radii plotted as dots. The color of the exoplanet dots aligns them with similar bodies in the Solar System: blue dots are exo-Saturns, green dots exo-Neptunes, and red dots exo-Venuses. Comparison of observations of Solar System bodies and exoplanets suggest that there is an empirically derived "cosmic shoreline" (denoted with a turquoise line), which divides those planets that are able to retain atmospheres from those that are not. The observed relationship implicates thermal escape processes as being key to atmospheric retention or loss. SOURCE: Zahnle and Catling (2017).

The interaction between planet and star can also fundamentally modify the composition of a planetary atmosphere through photochemistry, which in turn can impact climate by destroying or creating greenhouse gases. Photochemistry also contributes to atmospheric loss by removing H from high-altitude water vapor, allowing the H to escape to space. The stellar UV spectrum drives planetary photochemistry, and the resulting mix of gases depends on the initial atmospheric composition, the total amount of UV emitted by the star, and the wavelength dependence of the star's UV output (Meadows and Barnes, 2018). Consequently, to be able to interpret the impact of the star's radiation on planetary atmospheric composition, it is important to develop generalized photochemical/climate models to understand the diversity of terrestrial exoplanet environments. As input to these models, it is critical to characterize planetary host stars sufficiently to provide realistic high-energy stellar fluxes, both at the present time and over their history.

Life as a Planetary Process

Finally, it should be noted that life itself is a planetary process that can strongly impact the global environment; indeed, such changes lie at the heart of remotely detectable biosignatures. There are several examples in Earth's history where life has significantly modified the environment, with perhaps the most commonly known being the rise of atmospheric oxygen in the Great Oxidation Event at 2.3 Gya, due in part to the production of abundant O_2 by cyanobacteria (see review by Lyons et al., 2014). Consequently, it may be difficult to understand the evolution of a habitable terrestrial planet without understanding life's impact on planetary processes, and more research is needed in this area. More generally, the early Earth provides information on alien habitable environments with different atmospheric compositions and climates (Lyons et al., 2014), populated by metabolisms with potential biosignatures (Pilcher et al., 2003; Arney et al., 2018) that are very different to those produced by oxygenic photosynthesis on Earth today). These alternative Earth environments also inform the search for habitable exoplanets and biosignatures, as they may be more indicative of conditions found on other, especially younger, habitable exoplanets (Arney et al., 2017).

> **Finding:** The concept of the habitable zone has provided a first-order technique for identifying exoplanets that may be able to harbor life. A multiparameter holistic approach to studying exoplanet habitability, using both theory and observation, is ultimately required for target selection for biosignature searches.

Biosignatures

Understanding of biosignatures has advanced significantly (Kaltenegger et al., 2017; Schwieterman et al., 2018), but it still requires a significant investment to enable the search for life on exoplanets. While O_2 is considered the most well-studied biosignature to search for on terrestrial exoplanets (Meadows, 2017), and will likely be the first biosignature searched for, the field has expanded to encompass other biosignatures and supporting observations. There has been a growing understanding from studies of the early Earth (Reinhard et al., 2017), and exoplanet modeling efforts (e.g., Wordsworth and Pierrehumbert, 2014; Luger and Barnes, 2015; Domagal-Goldman et al., 2014; Gao et al., 2015; Harman et al., 2015), that biosignatures need to be interpreted in the context of their environment, as planetary processes may suppress, or even mimic, potential biosignatures (Meadows et al., 2018; Catling et al., 2018). In particular, there are two main questions that guide the future of exoplanet biosignature research:

- How are new potential biosignatures discovered?
- How is confidence in the interpretation of biosignature candidates increased?

Recent research, especially for O_2, has illuminated the nature of false negatives—namely, the destruction, removal, or sequestration of biogenic gases by the planetary environment—and false positives—namely, nonbiotic processes (primarily photochemistry of CO_2 or H_2O) that can generate O_2. These discoveries have driven the need to develop a comprehensive framework for biosignature identification and interpretation that takes into account confounding planetary processes (Meadows et al., 2018; Catling et al., 2018).

New potential biosignatures also need to be identified, and treated with the same rigor as O_2 as far as identification of false positives and negatives. The observational discriminants (including stellar characteristics) for processes that produce biosignature gases abiotically need to be further identified (e.g., Schwieterman et al., 2016). This research will inform measurement requirements and guide the development of tiered observing strategies to identify potential biosignatures, and systematically rule out abiotic processes that could have generated them.

Identifying New Biosignatures

There are multiple paths forward in identifying new biosignatures, and all involve interdisciplinary laboratory, fieldwork, and modeling. Research on existing Earth metabolisms could identify new biogenic gases or reflectivity signals that may dominate in environments different from modern Earth's (Schwieterman et al., 2015; 2018), and observations of modern Earth as an exoplanet can be used to search for global impacts due to life. Similarly, Earth's past can be explored using biological and geological constraints to understand the likely environments of the ancient Earth, and when particular metabolisms may have become dominant (Stüeken et al., 2017), to understand their potentially observable impact on the ancient environment that hosted them. Biological modeling of photosystems could also be used to improve predictions of how photosynthesis would be expressed for different planetary and stellar environments. Models that couple interactions between the planetary interior, surface, ocean, atmosphere, and biosphere can be used to look at the survivability of potential biosignatures in different contexts.

Agnostic biosignatures look for patterns of complexity or aspects of the environment that cannot be explained by normal planetary processes such as volcanism or photochemistry. The advantage of agnostic biosignatures is that they do not presuppose a known Earth metabolism, but their disadvantage is that the environment also needs to be characterized to be able to identify them. For exoplanets, possible agnostic biosignatures may include atmospheric and surface disequilibria, and the latter requires detecting the presence of an ocean, which is best done in direct imaging (Krissansen-Totton et al., 2016; Cowan et al., 2009; Robinson et al., 2010), or the complexity of atmospheric chemical networks (Walker et al., 2018).

Developing a Comprehensive Framework for Biosignature Interpretation

Increased confidence in the interpretation of biosignatures that may be observed is needed. In part, this confidence will stem from an ability to identify and rule out false positives. Additionally, understanding the variety of environmental contexts that can either strengthen or weaken the interpretation of planetary phenomena as biosignatures will be crucial. The following are key areas for future research to help develop this framework:

- Observing hot Earths (e.g., GJ 1132b, TRAPPIST-1 b, c, and d) to identify bulk atmospheric composition and photochemistry that may produce false positives for O_2.
- Determining likely false negative and false positive processes for biosignatures, and identify their observational discriminants.

A comprehensive observational framework would use signs in the planetary environment of the possibility of false negatives to inform target selection for biosignature searches. The subsequent search for life would then include not only the observation of the putative biosignature, but a search for false positive discriminants, as well as signs of secondary confirmation of the likely metabolism. For example, in the case of O_2, false positive discriminants include O_2-O_2 collisionally induced absorption (O_4; Hermans et al., 1999) and absorption from CO_2, CH_4, and CO, as well as a thorough characterization of the host star's UV spectrum. For a transiting exoplanet, time-resolved observation of refraction at transit ingress and egress with extremely large telescopes could also help identify vertical distribution of gases, to isolate photochemically generated O_2 in a planet's stratosphere (Misra et al., 2014). If the search for false positive indicators rules out several methods of abiotic production, then the interpretation of the potential biosignature detection becomes more credible. To make the detection even more convincing, a search could be made for secondary confirmation in the planetary environment of the likely metabolism—for example., in the case of oxygenic photosynthesis suspected due to atmospheric O_2, absorption from photosynthetic surface pigments, or seasonal variability in CO_2 or O_2 (or O_3; Olson et al., 2018) could provide corroborating information. These frameworks need to be developed for other biosignatures, and work to determine their observational feasibility for proposed telescopes needs to be undertaken. Specific investigations would include identifying and quantifying the abiological production processes for potential biosignatures such as methane, nitrous oxide, methyl chloride and others.

Bayesian methodology provides a language to define quantitatively the conditional probabilities and confidence levels of future life detection and may help constrain the prior probability of life with or without positive detection (Walker et al., 2018). The empirical and theoretical work described above will help place constraints on the relevant likelihoods, including those emerging from stellar and planetary context, the contingencies of evolutionary history and the universalities of physics and chemistry (Walker et al., 2018).

More generally, as in all truly new discovery space, humility is prudent when evaluating theoretical expectations about terrestrial planet atmospheres. An empirical census of atmospheres on terrestrial worlds under a wide range of conditions, both in and outside habitable zones, will be needed to validate or adjust current ideas about atmospheric signatures produced through abiotic and biotic processes.

> **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.

Discovering Potentially Habitable Planets and Searching for Life on Them

The methods and time scale for identifying potential habitable exoplanets and searching for atmospheric biosignatures are different depending upon the mass and size of the host star.

The M-Dwarf Opportunity

For M dwarfs, the low luminosities of the central stars mean that habitable zones correspond to short orbital periods, and the small sizes mean that the planets and their atmospheres can be detected by the transit method. Indeed, two nearby small stars are already known to host transiting planets that appear terrestrial (TRAPPIST-1, Gillon et al., 2017; LHS1140, Dittmann et al., 2017). Based on the high abundance of such stars and their proclivity to host rocky worlds (Dressing and Charbonneau, 2015), there should be several more systems nearby that will be discovered by Transiting Exoplanet Survey Satellite (TESS) and ground-based surveys. As described in Chapter 4, in the section “Opportunities to Characterize Planets Through Transits,” the atmospheres of such worlds could be observationally accessible with JWST and the giant segmented mirror telescopes (GSMTs), including the Extremely Large Telescope (ELT), the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT). Transmission spectroscopy of these targets will not be able to probe the near-surface atmosphere and planetary surface, but could reveal atmospheric constituents in the upper troposphere and stratosphere. As described in Chapter 4, in the section “The Case for Imaging,” there are also plans to study the atmospheres of the closer, nontransiting examples (such as Proxima Centauri b; Anglada-Escude et al., 2016) by imaging with the GSMTs. As discussed, M-dwarf terrestrial planets likely undergo very different evolutionary processes to terrestrial planets like Earth orbiting larger stars like the Sun. Yet, the majority of habitable-zone terrestrial planets in the galaxy orbit M dwarfs. M-dwarf exoplanets therefore hold the key to understanding prevalence of life beyond the Solar System. If planets orbiting M dwarfs are indeed able to harbor life, then life may be very common in the galaxy. The fact that targets are already known and that more will be found shortly, and the lack of a need to develop a large, high-contrast imaging space mission to pursue atmospheric studies, means that observational studies of potentially habitable worlds, including potential biosignature gases, could be under way by the mid-2020s.

The G-Dwarf Case

As described earlier, there are numerous reasons to think that the terrestrial worlds orbiting M dwarfs are not habitable; more generally, the need to extrapolate an understanding of habitability grows as one moves away from Sun-like stars. To complement the M-dwarf science case, the study of planets orbiting Sun-like stars will allow the study of planets that may have undergone evolutionary processes more similar to Earth, where it is known that life was able to arise. There is a compelling need to develop the means to detect and spectroscopically characterize temperate terrestrial planets orbiting Sun-like stars; however, the big sizes and large luminosities of such stars and the long orbital periods at the habitable zone mean that such work cannot be done with transit methods. Instead, as described in Chapter 4, in the section "The Case for Imaging," they require novel imaging space missions far more powerful than any in existence; if research begins now, this investment may bear fruit by the mid-2030s, roughly a decade after the M-dwarf opportunity. Importantly, the direct imaging missions will need to self-discover their own targets, unless these can be discovered in advance by precise radial velocity measurements. Direct imaging observations will potentially allow us to probe the entire atmospheric column and image the planetary surface to search for direct signs of habitability, such as the presence of an ocean.

Both transmission spectroscopy and direct imaging are sensitive to clouds and aerosols, although to differing degrees. High aerosols may stymie transmission observations that are taken through long slant paths in the upper atmosphere, but would provide less opacity to direct imaging observations. If the planet exhibits the partial cloud cover characteristic of convective condensate clouds on Earth, then direct imaging observations may also probe to the surface, even in the presence of clouds.

Requirements for Credible Interpretation of Biosignatures

In summary, the interpretation of biosignatures will likely need:

- An expanded interdisciplinary modeling, laboratory, and field effort to understand multifactorial habitability assessment and biosignatures assessment frameworks;
- Studies of a wide range of planetary atmospheres, from gas giants to uninhabitable terrestrials to improve understanding of the physical and chemical processes that modify planetary environments and provide the context for biosignature interpretation;
- An improved understanding of planet formation deep enough to allow use of a planet's system architecture, and the compositions of its sibling planets, as discriminants for biosignature assessment.
- Studies of terrestrial worlds that can proceed in the very near future for M dwarfs. For Sun-like stars, substantial investment will be required before observational studies can begin in earnest;
- Knowledge of the planet mass (yet researchers do not currently possess the ability to measure the masses of Earth-like planets orbiting Sun-like stars; see the section "Exoplanet Masses," in Chapter 4);
- Observational studies of the environments of planets being searched for biosignatures, including characterization of the parent star (see the section "The Need for Detailed Stellar Characterization," in Chapter 4), and other planets in the system; and,

- A multilevel approach to biosignature observations that uses environmental context to rule out false positives, and a statistical approach to assessment that quantifies the likelihood that a given phenomenon is due to life.

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4

Implementing the Exoplanet Science Strategy

EXPANDING THE STATISTICAL CENSUS OF EXOPLANETS IN THE GALAXY

As described in Chapter 2, although radial velocity (RV), direct imaging, and astrometry are all, in principle, sensitive to long-period planets, the microlensing technique is uniquely sensitive to low-mass planets at large separations—in particular, very low mass (mass greater than roughly two times the mass of the Moon) planets in orbits greater than roughly one AU—and analogues of the Solar System ice giants. It is therefore naturally complementary to the transit technique. However, it is not possible to achieve this full potential of the microlensing technique from the ground. Rather, to enable these capabilities, a space-based, near-infrared (NIR) mission with a relatively large field-of-view is required (Bennett and Rhie, 2002), for several reasons:

1. Microlensing events due to stellar lenses, which last a few days to hundreds of days, are both stochastic and rare, and thus require simultaneous monitoring of hundreds of millions of stars in order to detect a few thousand microlensing events. The only line of sight where this is possible given current technology is the galactic bulge, where the stellar surface density is approximately 20 million stars per square degree down to magnitudes of $H_{AB} \cong 21$. Thus, microlensing surveys require monitoring a few square degrees with a resolution of <0.3 arcsecond on time scales of a few days or less.
2. The perturbations of these microlensing events last from an hour to a few days, and have probabilities (given the existence of planet) of less than a few percent to tens of percent (for planets with the mass of the moon to the mass Jupiter). These perturbations are also stochastic, and thus require continuous monitoring of the microlensing events, at least ~15 minutes.
3. Given the crowded conditions of the galactic bulge, resolving the lens and source from unrelated background stars requires resolutions of <0.3 arcsecond. Once this resolution is achieved, it is possible to estimate the mass of the lens and the source for the majority of microlensing events (Bennett, Anderson, and Gaudi, 2006).
4. The ultimate limit to the mass of a planet that can be detected via microlensing is set by the angular size of the source. The smallest sources in the galactic bulge, M dwarfs, enable the detection of planets with mass as low as that of roughly 2 times the mass of the Moon. Given that M dwarfs emit the majority of their light in the NIR, given that the galactic bulge is generally heavily extincted, and given that the sky is very bright in the NIR from the ground, NIR surveys from space are optimal for microlensing surveys for exoplanets.

The WFIRST mission (Spergel et al., 2015) provides a nearly ideal architecture with the nearly ideal instrumentation needed to carry out the microlensing survey that enables a more complete statistical census of exoplanets in the Galactic bulge. Its combination of aperture, field-of-view, and NIR (H4RG) detectors are essentially optimal for this purpose. Figure 4.1 shows the sensitivity of a WFIRST microlensing survey, highlighting its nearly perfect complementarity to the Kepler survey.

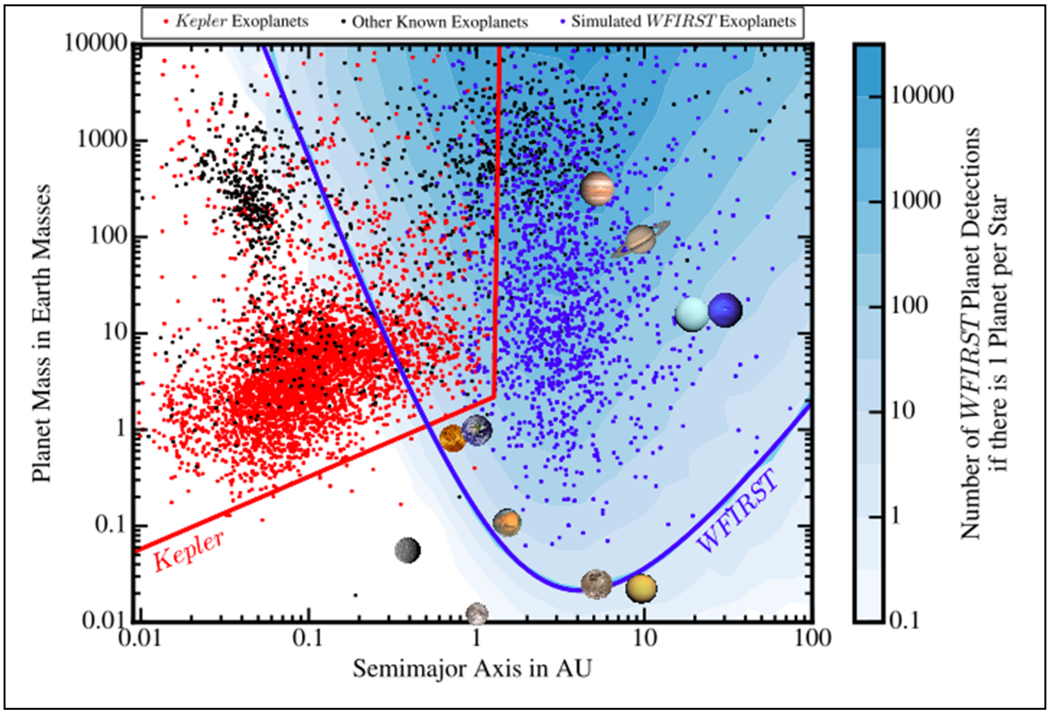

FIGURE 4.1 Comparison of the Wide-Field Infrared Survey Telescope (WFIRST) sensitivity to that of Kepler in the planet mass-semimajor axis plane. The red line shows an approximation of the Kepler planet detection limit based on Burke et al. (2015). Blue shading shows the number of WFIRST planet detections during the mission if there is one planet per star at a given mass and semimajor axis point. The thick blue line is the 3-detection per mission contour. Red dots show Kepler candidate and confirmed planets; black dots show all other known planets extracted from the NASA exoplanet archive. Blue dots show a simulated realization of the planets detected by the WFIRST microlensing survey, assuming a fiducial planet mass function (Cassan et al., 2012), although note that in constructing this sample of simulated detections, planets smaller than three times the mass of Earth or with semimajor axis less than 0.3 AU were not simulated. Solar System bodies are shown by their images, including the satellites Ganymede, Titan, and the Moon at the semimajor axis of their hosts. SOURCE: Images of the Solar System planets courtesy of NASA. Penny et al. (2018).

Although there are few strong constraints on the frequency, mass function, or separation distribution of planets with separations greater than roughly 1 AU, particularly for planets with the mass of Earth and smaller (indeed, this is precisely what WFIRST will measure), rough estimates of the number of bound planets WFIRST will find can be made by adopting current estimates of the planet mass distribution from ground-based microlensing surveys and modest extrapolations for planets with masses and separations outside the region of sensitivity of these surveys. The estimated yield is of order 1400 bound planets. In addition, again using relatively conservative assumptions, WFIRST should be able to detect hundreds of free-floating planets with masses as low as the mass of Mars. Assuming they originally formed in protoplanetary disks, measurements of the occurrence rate and mass function of free-floating planets provide a strong indicator of the dominant formation processes of exoplanetary systems.

The detections by WFIRST will be unambiguous and of very high significance. Figure 4.2 shows the simulated detection of a Ganymede-mass planet located at 5.2 AU from its parent star, and the detection of a potentially habitable planet. WFIRST may also be able improve upon Kepler's estimate of $\eta_\oplus$, the mean number per star of rocky planets with between 1 and 1.5-2 Earth-radii that reside in the habitable zone of their host star.

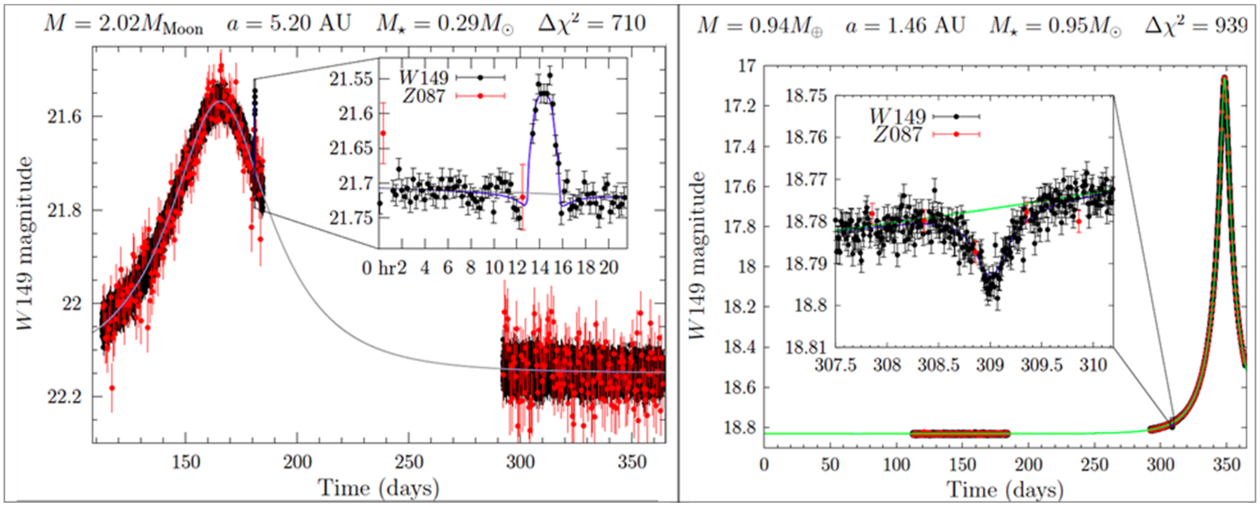

FIGURE 4.2 (Left) Example simulated detection of a 0.025 M_E (Ganymede-mass) bound planet detection from simulations of the most recent WFIRST design. Black and red data points are in the W149 and Z087 filters, respectively. The blue curve shows the underlying "true" lightcurve. (Right) Example simulated detection of an Earth-mass planet in the habitable zone of a Sun-like star. Although the expected number of detections of potentially habitable planets is small (given Kepler's current best estimate of $\eta_\oplus$), WFIRST may nevertheless be able to refine Kepler's estimate of $\eta_\oplus$ by extrapolating from the occurrence rates of more massive or more distant planets. Furthermore, assuming a mass/radius relation for potentially habitable planets, it may be possible to interpolate the results from Kepler and WFIRST to further improve the estimate of $\eta_\oplus$. SOURCE: Penny et al. (2018).

> **Finding:** A microlensing survey would complement the statistical surveys of exoplanets begun by transits and radial velocities by searching for planets with separations of greater than one AU (including free-floating planets) and planets with masses greater than that of Earth. A wide-field, near-infrared (NIR), space-based mission is needed to provide a similar sample size of planets as found by Kepler.

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

The recommendation regarding the WFIRST coronagraph is explained in the section "Space-Based Studies," later in this chapter.

Although a microlensing survey with the current incarnation of WFIRST is clearly the most capable and likely the most cost-effective mission to survey for exoplanets where the statistical census of exoplanets is most incomplete (Penny et al., 2018; Bennett and Rhie, 2002; Bennett et al., 2009), it is not strictly required to achieve the goals outlined above. The Microlensing Planet Finder, a proposed Explorer-class mission (Bennett al et al., 2010), could achieve the majority of these goals, as could the 1.1 m DRM2 incarnation of the WFIRST mission proposed by Green et al. (2012).

> **Finding:** If WFIRST is cancelled, a smaller, dedicated probe-class satellite could accomplish some of the science enabled by a space-based microlensing survey.

For the most part, a space-based microlensing survey would be self-contained, meaning that follow-up or concurrent observations would not be needed to extract the majority of the science from the survey. However, simultaneous observations from ground-based observatories such as the Large Synoptic Survey Telescope (LSST), the Korean Microlensing Telescope Network (KMTNet; Kim et al., 2016), or the Prime focus Infrared Microlensing Experiment (PRIME) telescope that is currently being developed (Bennett et al., 2018, white paper), could yield additional information about some of the detected planets, including the masses of free-floating planets (Zhu and Gould, 2016).

As described in the updated Exoplanet Exploration Program Analysis Group (ExoPAG) Study Analysis Group (SAG)-11 report "Preparing for the WFIRST Microlensing Survey," there are a number of activities that are needed to prepare for and optimize the WFIRST microlensing survey (Yee et al., 2014). These include a precursor NIR microlensing survey to determine the optimal location of the WFIRST microlensing fields (Shvartzvald et al., 2017), ground-based adaptive optics (AO) or Hubble Space Telescope (HST) data of past microlensing events to develop the technique that will be used by WFIRST to measure the masses of the host stars and their exoplanets, precursor simultaneous monitoring of microlensing events from Earth and from heliocentric satellites such as Spitzer or Kepler in order to measure microlensing parallaxes (Calchi Novati et al., 2015), precursor HST observations of the likely target fields to provide improved estimates of the microlensing event rates, and finally, building the (currently small) U.S. microlensing community through workshops, "hack weeks," making more microlensing data sets publicly available, and developing open-source, easy-to-use, and well-documented microlensing modeling codes (Poleski et al., 2018).

> **Finding:** A number of activities, including precursor and concurrent observations using ground- and space-based facilities, would optimize the scientific yield of the WFIRST microlensing survey.

THE CASE FOR IMAGING

A described in Chapter 2, direct imaging of exoplanets requires angularly resolving the planets from their host stars and directly detecting photons from the planets. Separating the planet's image from its host star is fundamentally limited by the theoretical diffraction limit λ/D, which is set by the observing wavelength λ and telescope diameter D. The large flux ratios and small angular separations imply that directly imaging and spectroscopically characterizing planets close to their host star requires dedicated high-contrast instruments.

Two complementary methods are required to achieve a very high-contrast direct detection using the traditional technique of internal coronagraphy: a coronagraph, which helps to suppress the diffraction from the host star, and wavefront control, which helps mitigate the effect of scattering arising from the combination of atmospheric turbulence (on ground-based telescopes) and time-varying optical aberrations in the telescope and instrument. Modern stellar coronagraphs consist of a series of masks inserted in the instrument pupil or focal plane. These masks are designed to remove the diffraction pattern from the central star as efficiently as possible, while preserving the signal of an off-axis object as close to the optical axis as possible. Roughly speaking, the inner working angle (IWA) of a coronagraph quantifies the smallest angular separation from the host star beyond which a planet of a given flux ratio can be imaged, and is often expressed in λ/D units. Formally, it is defined as the 50 percent off-axis throughput point. Naturally, the fundamental limit to the IWA is the theoretical diffraction limit λ/D. The details of a coronagraph's particular implementation are driven by the trade-off between IWA, contrast, and sensitivity to optical aberrations.

However, being static elements, coronagraphs do not allow for active control of scattered light induced by time-varying optical aberrations. That task is relegated to the wavefront control system, which is also known as the adaptive optics system on ground-based telescopes. Achieving a raw contrast of 10^{-5} at 1 micron requires controlling wavefront aberrations at the 1 nm root-mean-square (RMS) level. To accomplish this, the wavefront control system relies on a sensor, which can be a dedicated instrument or the science camera itself, and a correcting element. Most systems use actuated deformable mirrors for the

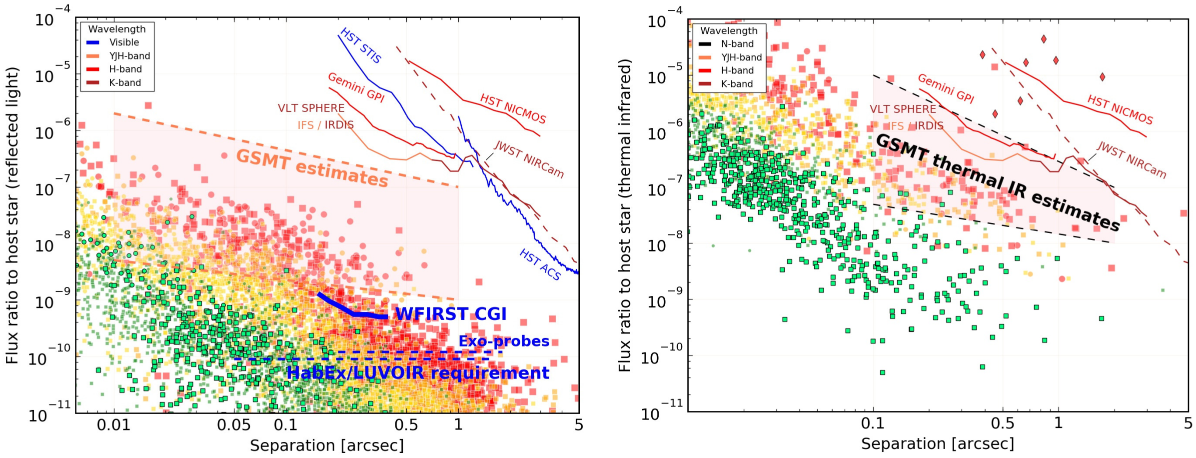

FIGURE 4.3 (Left) Reflected light flux ratio versus angular separation showing measured, estimated, and required contrast capabilities for current and future ground-based and space-based coronagraphs. (Right) Thermal emission flux ratio versus angular separation diagram showing measured, estimated, and required contrast capabilities for current and future ground-based coronagraphs. Note that in both panels, the large uncertainties pertaining to the giant segmented mirror telescope (GSMT) contrast curves range from a pessimistic case based on current facilities to an optimistic case that represents the promising high-contrast techniques currently under development. The various markers denote simulated planet populations within 27 pc using the SAG13 occurrence rates (Kopparapu et al., 2018) extrapolated up to a semimajor axis of 30 AU using an exponential cutoff. Another cutoff was applied to host star V magnitudes to reflect limitations in wavefront sensing capabilities from the ground and from space: V < 13 for cool stars observed from the ground (T_{eff} < 4000 K); V < 8 for warm stars observed with a space-based coronagraph (T_{eff} > 4000 K, left panel); V < 10 for warm stars observed in thermal emission from the ground (T_{eff} > 4000 K, right panel). In the left panel, a final cutoff was applied requiring cool-star planet magnitudes to be <32, and warm-star planet magnitudes to be <35, which represents the optimistic photon noise limits for a GSMT in J band in 100 hours, and a 9-meter space telescope in V band in 300 hours. In the right panel, a final cutoff was applied requiring planet magnitudes to be <22 at N band (10.5 microns), which represents the optimistic photon noise limits for a GSMT in N band in 30 hours. In both panels, the marker size is proportional to the planet size: red for giant planets (radius > 6 R_E); orange for Neptunes (6 > R_E > 3.5); yellow for mini-Neptunes (3.5 > R_E > 1.75); dark green for super-Earth and Earth-size planets (1.75 > R_E > 0.5); and light green for temperate ([0.7*sqrt(L/L_{Sun}), 1.5*sqrt(L/L_{Sun})] AU) super-Earth and Earth-size planets. The round markers are for planets around cool stars (T_{eff} < 4000 K), while the square markers denote planets around warmer stars (T_{eff} > 4000 K). In the right plot, the diamonds denote young giant planets discovered by current ground-based adaptive optics facilities. Caveat: Being above a contrast curve does not necessarily mean detection as a single plot cannot capture the very diverse detection capabilities of all coronagraphic instruments illustrated here. SOURCE: D. Mawet (Caltech), B. Macintosh (Stanford), T. Meshkat (IPAC/Caltech), V. Bailey (JPL/Caltech), D. Savransky (Cornell).

correcting element. The challenge of the wavefront controller is to sense and correct the aberrations within the time scale associated with the change of the perturbation. This requirement sets another fundamental limit on the achievable contrast—the brightness of the host star used for sensing—and its corresponding photon shot noise over the time scale of the stability of the system (telescope and instrument).

Most direct imaging detections of exoplanets so far have relied on the combination of adaptive optics and coronagraphs on ground-based telescopes. Due to the turbulent nature of Earth's atmosphere, the main purpose of the wavefront controller is to correct for the large and rapidly evolving wavefront aberrations induced by the propagation of waves through the turbulent medium of the atmosphere. The most modern incarnations of adaptively corrected ground-based coronagraph instruments are currently limited to contrast ratios of about 10^{-6} (Figure 4.3), which is sufficient to detect the glow of young forming giant planets that are emitting thermal infrared due to their ongoing contraction from formation.

Because they will push the boundaries of the aforementioned fundamental trade-offs to new and distinct regimes, the advent of giant adaptively corrected ground-based telescopes and (ultra-)stable active space-based coronagraphs presents a game-changing opportunity for the direct imaging and characterization of exoplanets.

Ground-Based Studies

The Giant Segmented Mirror Telescope Opportunity

The advent of GSMTs will provide new opportunities for exoplanet imaging and characterization in the next decade (Gilmozzi and Spyromilio, 2007; Johns et al., 2012; Sanders et al., 2013; Wang et al., 2017). Two of these GSMTs—namely, the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT), are U.S.-led efforts, which together will cover the entire night sky. Both are actively seeking funding to complete the projects, including funding from the NSF. The 3-fold improvement in angular resolution, 10-fold improvement in light-collecting capabilities, and 80-fold improvement in sensitivity to point sources provided by 30-meter class facilities will open up new vistas of exploration. From the detection and spectroscopic study of gas and ice giants in reflected light and thermal emission, to the search for biosignatures of rocky planets orbiting M-type stars, direct imaging provides complementary phase space coverage to indirect methods and is the only technique capable of spectroscopically characterizing nontransiting exoplanets (Fitzgerald et al., 2018, white paper).

Young Self-Luminous Planets

GSMTs will provide a unique opportunity to survey nearby young planetary systems within the "ice line" ($a \sim 3$ AU), and bridge the separation gap with Doppler RV and transit surveys. High-resolution spectroscopy with GSMTs will also enable the measurement of planet spins (Snellen et al., 2014; Bryan et al., 2018) and in some cases Doppler imaging studies, as in Crossfield et al. (2014).

Mature Giant Planets in Reflected Light with GSMTs

GSMTs will enable the direct imaging of mature gas giant and ice giant planets in both reflected light and thermal emission (Figure 4.3). RV surveys will provide promising targets for follow-up imaging and characterization studies. Moderate or high-resolution spectroscopy will probe the depths of multiple water and methane features, allowing models to recover carbon or oxygen abundances and, in turn, enable integrated studies of abundances versus planet location, mass, and host star properties (Lupu et al., 2016).

Search for Life Around M-Type Stars

The contrast ratio between a temperate Earth-size planet and a Solar-type stellar hosts is 10^{-10}. This contrast ratio requires deep levels of starlight suppression that are beyond the fundamental limits of ground-based AO systems. Contrast limits are indeed set by the finite number of photons available for sensing and correcting wavefront aberrations induced by quickly evolving atmospheric turbulence (Guyon, 2005; Poyneer et al., 2007; Guyon, 2017; Males and Guyon, 2018). GSMTs will, however, be able to detect starlight reflected by rocky, habitable-zone exoplanets around the nearest M dwarfs. Indeed, the low luminosities of M dwarfs means that planets need to orbit close to the star to receive Earth-like radiance levels, and so the contrast ratio is relaxed by several orders of magnitude to 10^{-7}-10^{-8}. However, while the proximity of M-dwarf habitable zones to the star currently poses a challenge for direct imaging because the habitable zone lies well inside the IWA of 8 m class telescopes, the small IWAs enabled by 30-meter class telescopes (roughly 10 mas around 1 micron) make them ideal facilities for characterizing planets in the habitable zones of M dwarfs (Figure 4.3). GSMTs will be powerful facilities not only in obtaining more complete and less biased statistics on planetary demographics through surveys that image planets orbiting low-mass stars but also in characterizing these discoveries. Together with the James Webb Space Telescope (JWST), high-contrast AO observations will be among the first opportunities to detect biosignatures in the atmospheres of other worlds. Planets around faint M-type stars are favorable targets for spectroscopic follow-up at shorter wavelengths with both GSMTs. There are abundant lines from biosignature gases, O_2, H_2O, CH_4, and CO_2, in the near infrared (roughly 1-4 μm), also where the High Dispersion Coronagraphy technique is expected to reach optimal performance (see below). There are roughly 20 M dwarfs within 5 pc that are observable by GSMTs, and there is at least one rocky planet per M dwarf (Dressing and Charbonneau, 2015) with one in four potentially in the habitable zone. Given the limited number of targets available and the likely different scientific emphasis of the two U.S.-initiated GSMT programs, access to the full sky through telescopes in both hemispheres is important, and investment in both GSMT projects is preferred.

> **Finding:** The GMT and TMT will enable profound advances in imaging and spectroscopy of entire planetary systems, over a wide range of masses, semimajor axes, and wavelengths, potentially including temperate Earth-size planets orbiting M-type stars.

Thermal Infrared Studies

Thermal infrared observations with GSMTs may allow detection of warm (T = 400-600 K) rocky planets around the nearest (<5 pc) FGK stars (at 3-5 μm; Crossfield, 2013), as well as somewhat cooler Earth-size rocky exoplanets around nearby Sun-like stars (at 8-13 μm; Quanz et al., 2015). At the longest wavelengths, biomarkers such as H_2O, CH_4, O_3, and CO_2 can be identified using low-resolution spectroscopy (Des Marais et al., 2002). The spectral energy distribution can additionally be used to estimate surface temperature and cloud fraction. For T = 400 K super-Earths around K-stars, GSMTs will be able to spectroscopically characterize both reflected light and 3-5 μm thermal emission for the same planets. The same will be true for some of the known, nearby, close-separation RV-detected rocky terrestrials, super-Earths, and warm giants (ice and gas) at 10 μm. Combining measurements of thermal and reflected light will make GSMTs the first instruments capable of measuring the radii and studying the energy budget and climate of other worlds (Fitzgerald et al., 2018, white paper; Meyer et al., 2018, white paper). The GMT and TMT may image and spectroscopically characterize the nearest temperate Earth-size planets orbiting G-type stars in the thermal infrared.

A Technological Roadmap for Ground-Based High-Contrast Imaging

High-contrast characterization of exoplanets from the ground, a prime science case for GSMTs, still requires substantial technology developments. The gap between second-generation AO systems on current 8-10 m class facilities and the requirement for imaging and characterization of Earth-like planets around M-type stars constitutes several orders of magnitude of improvement in contrast. A vigorous research and development (R&D) program involving specific laboratory activities and on-sky demos spread over the next decade is necessary to fill in technology gaps (Currie et al., 2018, white paper).

Breakthroughs in Extreme Adaptive Optics and Wavefront Control

The challenge in reaching the full potential of GSMTs for reflected-light spectroscopy appears twofold—namely, pushing the raw contrast ratio to more extreme values from the current state of the art of 10^{-4}-10^{-5} to 10^{-7}-10^{-8}, and extending the effective IWA toward the diffraction limit of the telescope (λ/D). Fundamentally, these stem from a single driving requirement: to adequately sense and control wavefront aberrations—in particular, low-order aberrations that dominate the raw contrast error budget at small inner working angles (see white papers from Fitzgerald et al., 2018 and Currie et al., 2018). Current wavefront control architectures are nowhere near their fundamental photon noise limits (Guyon, 2005) because they are hampered by noisy detectors, suboptimal sensing-to-command conversion efficiencies, including control laws (simple integrators to linear predictors; see Males and Guyon, 2018), and the time lag between the wavefront measurements and the application of the correcting command. Relatively recent architectures such as Pyramid and focal plane wavefront sensors have started to surface in adaptive optics facilities (e.g., Jovanovic et al., 2015) and hold the promise of both optimal conversion efficiencies and controlling rapidly fluctuating wavefront errors including noncommon path aberrations. Developments in predictive control and sensor fusion show promise to break through the practical limitations of present-day AO systems, currently limited to 10^{-4}-10^{-5} raw contrast, and bring us closer to the 10^{-7}-10^{-8} requirement to image and characterize temperate Earth-size planets around M-type stars (Poyneer, 2007; Guyon and Males, 2017; Males and Guyon, 2018).

Considerable uncertainty remains in the maximum achievable performance of high-contrast adaptive optics systems on the GSMTs, and that uncertainty spans the range that will allow detection of potentially habitable planets. Development of better simulation tools, prototyping of concepts on laboratory and 8-10 m class facilities (see below), and maturation of conceptual instrument designs will be crucial to determining the final architecture and capabilities of a GSMT planet imaging facility. Involvement by the U.S. community and the National Science Foundation (NSF) in the two GSMT projects will help to enable that.

High-Density Deformable Mirrors

The enabling hardware technology for GSMTs are fast (>kHz), large-stroke (>6 microns), high-order (120 × 120 actuators) deformable mirrors. Planet imager instruments on GSMTs will directly benefit from a recently concluded R&D effort initiated by European Southern Observatory for the Extremely Large Telescope (ELT). The outcome of this study and other efforts currently carried out in the industry is a clear path to fulfilling the requirements.

Coronagraphs for Segmented and Obscured Apertures

Thanks in part to the WFIRST-Coronagraph Instrument (WFIRST-CGI) technology development program and the difficulties associated with the heavily obscured WFIRST telescope aperture, as well as the Segmented Coronagraph Design Analysis (SCDA) initiated by the Exoplanet Exploration Program (ExEP) for Large UV/Optical/IR Surveyor (LUVOIR) and Habitable Exoplanet Imaging Mission (HabEx), there are now coronagraph technologies and design tools readily applicable to GSMTs. Coronagraph technologies have significantly evolved over the past 10 years such that the challenge of designing and building a coronagraph that is insensitive to segmented/obscured apertures and low-order wavefront errors has largely been overcome.

High-Dispersion Coronagraphy

High-dispersion coronagraphy aims to optimally combine high-contrast techniques with high-resolution spectroscopy (Ruane et al., 2018, white paper). This rapidly developing technique, which leverages advances in extreme precision RV spectrographs (see the section “Radial Velocities,” later in this chapter), is still in its infancy but promises to help bridge the contrast gap mentioned above by sidestepping speckle noise, which is one of the most pervasive sources of systematics. The technique searches for specific spectral features in either thermal emission or reflected light that are unique to the planet. It multiplies the contrast ratio achieved by high-contrast imaging by the additional contrast realized by high-dispersion spectroscopy. Implemented on GSMTs, it has the potential to find and atmospherically characterize temperate terrestrial planets around the most nearby stars. Since it is inherently sensitive to Doppler effects induced by the orbital motion of the planet (10-100 km/s; see, e.g., Snellen et al., 2014; Hoeijmakers et al., 2018), it allows for an effective separation of the suite of planet molecular lines in a given absorption band from those produced in Earth's atmosphere, enabling the search for interesting species such as H_2O, CH_4, CO_2, and O_2.

While current facilities have helped to provide a glimpse of the power of this recent method (Konopacky et al., 2013; Snellen et al., 2014; Bryan et al., 2018; Crossfield et al., 2014), no facility fully integrating high-contrast spectroscopy has yet seen the light. Several ongoing projects at the Very Large Telescope (VLT; Lovis et al., 2017), Subaru telescope (Jovanovic et al., 2017), and Keck telescope (Mawet et al., 2017) are noted that will help assess the relevance of the technique to future GSMT facilities.

Polarimetry

Polarimetry is a useful tool for the characterization of directly imaged exoplanets (Millar-Blanchaer et al., 2018, white paper). Polarimetric observations with future telescopes have the potential to refine understanding of scattering processes in the atmospheres and on the surfaces of planets. In particular, time-series and spectropolarimetric measurements can distinguish between different cloud and surface types. Notably, polarimetry has the ability to constrain planetary albedos and may ultimately be able to reveal the presence of a liquid water surface (Williams and Gaidos, 2008). Relatively little attention has been given to polarimetry within the exoplanet community to date. This is due in part to the difficulty of obtaining high signal-to-noise ratio polarimetric measurements with current facilities, and to the lack of existing polarimetric detections. To maximize the gain from polarimetric measurements, careful attention needs to be paid to the design and implementation of future instrument designs. For example, an instrument able to suppress unpolarized speckles by a factor of 1000 (similar to current Gemini Planet Imager [GPI] and Spectro-Polarimetric High-Contrast Exoplanet Research [SPHERE] instrument levels; see, e.g., Millar-Blanchaer et al., 2016; van Holstein et al., 2017) will gain a factor of 50 in detection limits relative to the raw contrast for a 5 percent polarized planet. For reference, Earth is up to approximately 30 percent polarized at 0.5 μm (Coffeen, 1979).

High Quantum Efficiency, Low-Noise Detectors

High quantum efficiency (QE), low-noise (<1 e-) or zero-noise detectors will be needed to approach the fundamental limits of wavefront sensing and scientific measurements. The arrival and on-sky testing of new low-noise fast-readout detectors, such as microwave kinetic inductance detectors (MKIDs) and infrared avalanche photodiode (IR-APD) arrays, have enabled much more powerful focal-plane wavefront sensing techniques (Meeker et al., 2018; Atkinson et al., 2014). These detector technologies still have a long way to go to form the backbone of future scientific instrumentation. For instance, their format is still confined to small arrays (e.g., 320 × 256), which is sufficient for wavefront control, but precludes their use in conventional imagers and spectrographs.

Science and Technology Pathfinders on Existing 8 to 10 Meter Class Facilities

Ground-based telescopes have been playing a leading role in exoplanet direct imaging science and technological development for the past two decades and will continue to have an indispensable role for the next decade and beyond. Extreme adaptive optics (AO) systems will advance wavefront control, coronagraphy, and post-processing, thereby augmenting the performance of and mitigating the risk for WFIRST-CGI, while validating performance requirements and motivating improvements to atmosphere models needed to unambiguously characterize Solar System analogues with HabEx/LUVOIR (Currie et al., 2018, white paper). Current facilities are also the proving ground to develop technologies for future GSMT instruments focused on exoplanet imaging and spectroscopic characterization.

Finding: The technology roadmap to enable the full science potential of GMT and TMT in exoplanet studies is in need of investments, leveraging the existing network of U.S. centers and laboratories and current 8-10 meter class facilities.

Recommendation: The National Science Foundation (NSF) should invest in both the GMT and TMT and their exoplanet instrumentation to provide all-sky access to the U.S. community.

The committee further notes that an additional finding in support of this recommendation appears at the end of the section "Opportunities to Characterize Planets Through Transits," later in this chapter.

Space-Based Studies

Direct imaging with a space-based telescope has long been recognized as one of the most promising paths to spectroscopically characterize planets around Sun-like stars (Malbet et al., 1995; Angel and Burrows, 1995). In space, wavefront aberrations are caused only by the instrument itself, and can be stable or evolve very slowly. For a sufficiently stable telescope, deformable mirrors can provide essentially perfect correction. Since space telescopes are (necessarily) smaller than their Earth-bound counterparts, diffraction control is critical to achieving a reasonable IWA, but a wide variety of coronagraph concepts have been developed to address this requirement (Guyon et al., 2006).

In the early part of the 21st century, an architecture known as the Terrestrial Planet Finder Coronagraph (TPF-C) emerged as a mission concept (Trauger and Traub, 2006). It would have combined a 3 × 8 m elliptical monolithic mirror with a visible-light active optics coronagraph to achieve the flux ratio sensitivity of $\sim 10^{-10}$ at ~0.08 arcsecond IWA required to detect and characterize Earth-like planets.[1] Although understanding of coronagraphy has advanced enormously since then, and TPF-C was never selected as a mission, it remains the prototype for the planet-characterizing missions now on the drawing board. These missions remain exceptionally challenging, requiring exquisite optical stability and sophisticated components, but are feasible with current technology.

Such concepts are often referred to as "internal" coronagraphs, since the scattered starlight is controlled by components, such as coronagraphic masks and deformable mirrors, located inside the telescope spacecraft. Another concept that was originally proposed decades ago (Spitzer, 1963) but that has seen enormous recent advances is the "external" coronagraph (Cash, 2006), usually referred to as a "starshade," which blocks the target star with a large (20-70 m) free-flying occulter. The occulter is designed to minimize diffracted light, while allowing the off-axis planet to be imaged directly. The inner working angle of a starshade system is set by the geometry of the system, roughly the ratio of size of the starshade to the distance to it, and hence is somewhat decoupled from the telescope diameter, although practical and optical considerations often limit achievable inner working angles to roughly the telescope diffraction limit for 4 m telescopes. This still improves the practical IWA by a factor of 2 to 3 over internal coronagraphs. The shape of the starshade needs to be specially designed to control diffracted starlight, thereby casting the deepest possible shadow. Starshades are well suited to small to medium-size (1-4 m telescopes), giving them similar IWAs to larger telescopes with internal coronagraphs, but this comes at the cost of operational flexibility. In addition, current technology generally allows starshades to have larger outer working angles (OWAs) than internal coronagraphs, as the OWA of a starshade is set by the size of the detector, whereas the number of actuators in the deformable mirrors set the OWA of an internal coronagraph. The above-mentioned concepts have somewhat complementary capabilities, with internal coronagraphs being more agile and easily retargeted, while starshades have high throughput over

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[1] A parallel interferometer-based concept, TPF-I, was designed for mid-IR operations; see https://exoplanets.nasa.gov/exep/resources/documents/.

a broad spectral bandpass, and have very deep shadows, and thus can characterize extremely faint planets; some mission concepts combine both modes to take advantage of this complementarity.

A high-contrast imaging mission would combine starlight control (coronagraph or a starshade) with a suite of scientific instruments. Notionally, these would include an imaging camera (optimized for rapid detection of planets, measurement of their orbital motions, and broad photometric characterization); an imaging spectrograph such as an integral field unit (for obtaining low-resolution spectra of the vicinity of target stars, and to identify molecular species in planetary atmospheres); and perhaps a polarimetric capability (see the preceding section, "Ground-Based Studies") for further characterizing planetary clouds or circumstellar dust. Imaging spectroscopy is broadly similar to transit spectroscopy (see the section "Atmospheric Characterization Through Transit Spectroscopy," later in this chapter), but because it does not require the "slant geometry" of transit spectroscopy, it is less sensitive to high-atmosphere clouds and hazes. Thus, directly imaged spectra potentially allow for the detection of molecular species in cloudy planets (Robinson et al., 2006). The fundamental and practical limitations of coronagraphs and starshades likely limit missions to the UV/Optical/NIR region.

Science Case for Space-Based High-Contrast Imaging

Space-based direct imaging is capable of a wide variety of scientific programs in the study of extrasolar planets. A well-designed direct imaging space mission would address a range of the key questions identified in this report.

Characterization of Mature Exoplanets in Reflected Light

Space-based direct imaging will be able to access mature giant planets, Saturn-size or smaller, from approximately 0.5 to 15 AU. Space-based coronagraph imaging is a powerful complement spectroscopic characterization with JWST, which will characterize giant planets close to their stars. Spectroscopy can constrain atmospheric properties such as methane abundance (Figure 4.4). With the combination of both missions, it will be possible to study planets whose different locations imply different formation histories, and whose different temperatures access different chemistries at different atmospheric depths.

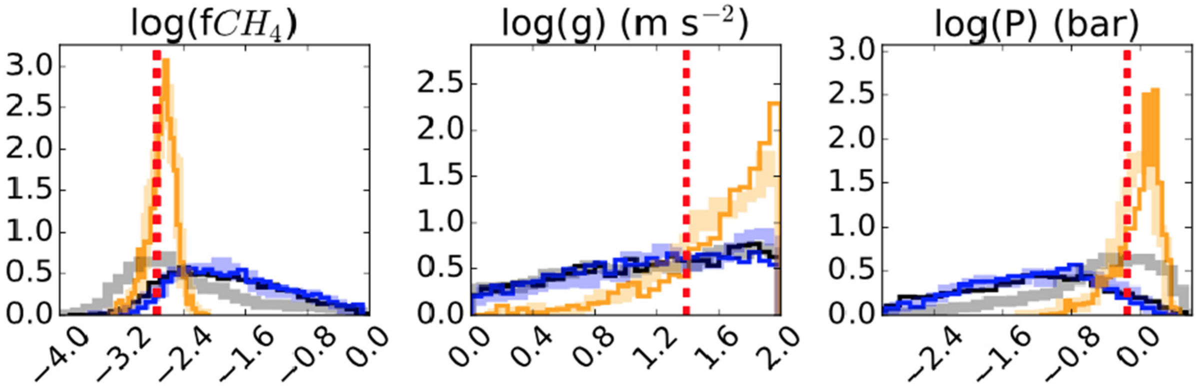

FIGURE 4.4 Results of retrieval studies on simulated reflected light data of directly imaged Jupiters demonstrate the fidelity with which basic properties of a Jupiter-like exoplanet (vertical red dashed line) can be constrained. Panels show, from left, the precision to which the logarithmic atmospheric abundance of CH4, gravity, and cloud-top pressure can be retrieved from moderate-resolution reflected light spectra (R ~ 50-70) with SNRs of 5 (blue/black), 10 (gray), and 20 (yellow). SOURCE: R. Lupu from Marley et al. (2018), white paper.

Since giant planets are relatively bright, missions capable of discovering Earth-equivalent planets can easily characterize a large sample of giant planets. Most of them will already be known through RV or astrometric surveys (see the section "Exoplanet Masses," later in this chapter), making this approach a straightforward, high-reward science program early in any direct imaging mission. Such observations will also be capable of characterizing "super-Earth" planets over a narrower range of separations (approximately 0.5-3 AU), again complementing the sample of super-Earths close to low-mass stars. For example, detection of atmospheric constituents could help determine whether these planets have primordial hydrogen-dominated atmospheres or secondary atmospheres.

Search for Earthlike Planets Around Solar-Type Stars

Detecting an Earth-size planet in the habitable zone of a Sun-like star at a distance of 10 pc in reflected light requires detecting a planet with a flux ratio of roughly 10^{-10} (equivalent to a V = 30 magnitude star) less than 0.1 arcsecond away from a V = 5 magnitude star. Daunting as this is, high-fidelity simulations indicate it is within the reach of a properly optimized space telescope. Such measurements are essentially impossible with any other technique; it is extremely unlikely that such a planet will be found to transit any nearby star, and even if it did, accumulating enough transits to characterize the atmosphere of the planet (which would produce a signal of roughly 0.1 percent of the transit depth, which itself is 0.01 percent), would obviously take many years. Ground-based extremely large telescopes, although capable of imaging at very small IWAs, will be unable to reach these contrast levels (see the section "Ground-Based Studies," earlier in this chapter). A large space-based direct imaging mission, using either the coronagraph or starshade starlight suppression techniques, is the best path to finding an "Earth twin" in the next two decades.

> **Finding:** A coronagraphic or starshade-based direct imaging mission is the only path currently identified to characterize Earth-size planets in the habitable zones of a large sample of nearby Sun-like stars in reflected light.
>
> **Finding:** Recently acquired knowledge of the frequency of occurrence of small planets, and advances in the technologies needed to directly image them, have significantly reduced uncertainties associated with a large direct imaging mission.[2]

As with giant planets, determining the nature of an Earth-size planet will require spectroscopic characterization. Similar techniques can be applied—for example, simulated retrievals indicate that high signal-to-noise ratio (SNR) moderate-resolution (R > 70) visible-light spectra can determine atmospheric abundances of O_2 and H_2O (Feng et al., 2016). However, determining whether a world is truly life-bearing may require additional study beyond the identification of molecules. Multiple observations will allow determination of the orbit of a planet and (when combined with Doppler measurements) the mass of a planet. More capable coronagraphic or starshade missions can also access NIR or UV wavelengths, allowing species such as CH_4 to be measured. It is important to emphasize, however, that unless observers are very fortunate, no single mission is likely to be able to identify life, or even a habitable world, with high confidence. Once these first discoveries are made, they will, instead, guide future observations and the design of more capable future missions that will shape the understanding of these new worlds.

Architecture of Mature Exoplanetary Systems

Imaging a planetary system can provide (almost by definition) a portrait of multiple members of a planetary family. Such a portrait could show many of the planets within a given system. Follow-up observations will determine their orbits (co-planarity, stability, etc.). In addition, circumstellar dust from

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[2] See later in this section for further discussion.

smaller bodies—analogous to zodiacal light near Earth—will likely be detectable, providing information on the small-body population and mass constraints on both seen and unseen planets. For example, the masses of the planets seen in the directly imaged systems HR8799 and Beta Pictoris are constrained by dynamical interactions between multiple planets or dust disks (Fabrycky and Murray-Clay, 2010). In the youngest systems, these disks are thousands of times brighter than the Solar System's and easily detected, particularly in the outer portions of stellar systems. Future coronagraphic missions will approach the level of sensitivity needed to see mature disks; simulations predict that the WFIRST coronagraph could detect roughly 10 times the solar level of scattered light (Mennesson et al., white paper).

Near-Term Imaging with JWST

Although it will carry a suite of coronagraph masks for different modes and wavelengths, the James Webb Space Telescope (JWST) has not been optimized for high-contrast imaging. It will have similar capabilities to ground-based AO instruments for studying young giant planets. JWST will be able to detect lower mass (Saturn-like) or low-entropy planets (Fortney et al., 2006; APJ 683) by observing at longer wavelengths where they are brightest, but at slightly larger IWA than the most advanced ground-based systems (Beichman et al., 2018, white paper). Discovering a significant number of Saturn- to Jupiter-mass planets will require a large-scale systematic survey and could be a key JWST giant-planet result. Combining JWST mid-infrared (MIR) observations with ground-based spectroscopy will allow precise determination of planetary luminosities and temperature.

Sensitivity Scaling with Telescope Diameter

The capability of a large space mission to discover any given planet type depends on its inner working angle and contrast, and also on its total sensitivity. Planets are extremely faint; even with starlight perfectly blocked, adequate spectroscopic characterization requires a large photon collection rate and, thus, a large aperture or high throughput.

The discovery process is quite complex—a single observation may fail to find a planet in an edge-on orbit if it is passing almost in front of or behind its parent star, for example. Target selection, exposure time selection, timing of observations to confirm a candidate, and so on, are a complex optimization problem that has been extensively studied (Stark et al., 2015; Garrett et al., 2017; Brown, 2004). Nonetheless, with the increasing confidence in planetary occurrence rates and increasingly sophisticated strategies, researchers can now forecast the likely yield of Earth-size habitable zone (HZ) planets within a factor of roughly 2. Adjustments to optimization strategies and criteria may vary planet yields, particularly the number of planets for which a high-SNR spectrum can be obtained, but the overall relative capabilities of missions of different scales are unlikely to vary significantly from these estimates.

Figure 4.5 shows the general trend of the number of habitable zones surveyed for potentially Earth-like planets (discovery and spectroscopic characterization) by notional coronagraph missions versus telescope inscribed diameter and architecture, based on exoplanet occurrence rates from the NASA ExoPAG SAG-13 activity (Kopparapu et al., 2018). In addition to telescope diameter, sensitivity is a function of telescope architecture. Off-axis telescopes, without a secondary mirror obscuring part of the pupil, can incorporate coronagraphs that can operate at small inner working angles with high throughput. Small obscurations such as gaps between hexagonal telescope segments do not significantly degrade the yield. Larger features such as a secondary mirror, particularly when combined with realistic wavefront jitter such as vibration-induced tip/tilt, restrict the telescope to lower performance coronagraphs such as apodized pupil Lyot coronagraphs (APLCs). These limitations may not be fundamental but have not yet been overcome in spite of extensive exploration of coronagraph concepts. In Figure 4.5, the two lines correspond to high-performance coronagraphs suitable for telescopes without secondary mirrors, and lower performance coronagraphs for very large conventional telescopes. The figure shows that missions now under consideration have a high probability of yielding spectra of many Earth-analogue planets in the habitable zones of intermediate-mass stars.

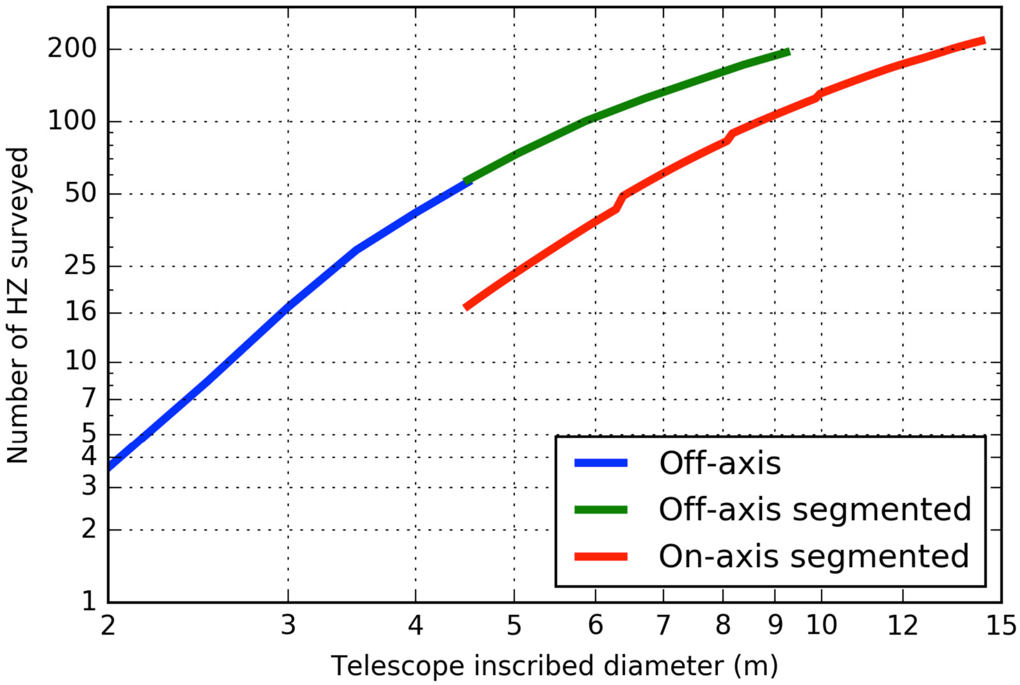

FIGURE 4.5 The total number of habitable zones (HZs) surveyed (weighted by observational completeness) for potentially Earth-like planets (small terrestrial planets in the classical HZ of their star) versus telescope-inscribed diameter for both off-axis telescopes that can employ more efficient coronagraphs, such as the vortex coronagraph (VC), and more conventional on-axis telescopes combined with an apodized pupil Lyot coronagraph (APLC). The on-axis case (red curve) may increase as on-axis coronagraph designs continue to improve. This plot is for missions that use a coronagraph for detection and orbit determination with targets selected to allow spectroscopic characterization. Note that current estimates of the occurrence rate of Earth-size planets in the habitable zone is approximately 0.24 planet per star (Kopparapu et al., 2018).

Roadmap for Direct Imaging

The overall path to direct imaging of Earth-like planets is relatively clear through currently active programs and missions to be proposed to the 2020 Decadal Survey.

First, the WFIRST mission will carry a technology demonstration coronagraph to advance readiness for future missions. The NASA Technology Demonstration for Exoplanet Missions (TDEM) program continues to support laboratory development of technology for future missions, including advanced coronagraphs suitable for the telescope designs of the next major mission, validation of starshade concepts and technology, and key components such as low-noise detectors.

During the decade of the 2020s a probe-class starshade could be launched to rendezvous with WFIRST and carry out a strong science program, characterizing a diverse set of planetary systems while potentially searching for Earth analogues around the nearest stars. If the WFIRST mission loses the coronagraph or starshade capabilities, a stand-alone probe-class coronagraph launched late in the decade could fill the gap between current capabilities and the large strategic mission, laying scientific groundwork and validating technical approaches.

In the same decade design would begin on a direct imaging mission for launch in the 2030s, based around the large strategic mission concepts of HabEx or LUVOIR. It would be capable of detecting and characterizing a significant sample of Earth-size HZ planets. Characterization would include high-SNR spectroscopy to determine abundances of O_2, O_3, H_2O, and, if possible, CH_4 for a subset of the closest targets. The mission would also enable a balanced exoplanet science portfolio through studies of planetary system architectures (with sensitivity to true Solar System analogues), metallicity and atmospheric properties of giant planets, atmospheric diversity of super-Earth planets inside and outside the habitable zone, density and structure of circumstellar dust, and the properties of young planet-forming systems. Combined with characterization such as planetary mass measurements from other facilities, this mission could provide a comprehensive picture of the evolution of planetary systems and may provide the first evidence of a habitable Earth twin—an epochal moment in human history.

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.

WFIRST Opportunity

The WFIRST mission (Spergel et al., 2015) has gone through a series of evolutions of its direct imaging capability. Originally conceived by the 2010 Decadal Survey as a wide-field imaging mission on a 1-1.5 m telescope (ASTRO2010), with exoplanet science focused on microlensing, it was redesigned based on the addition of a newly available 2.4 m telescope assembly. In addition to enhancing the core science capabilities, this telescope was large enough to potentially carry a coronagraph. Such a coronagraph would both satisfy the 2010 Decadal Survey mandate for advancing coronagraph technology and could carry out a significant science mission characterizing giant planets and zodiacal dust disks. The telescope was not ideal for coronagraphy, with a large and complex secondary mirror structure and other complications such as large reaction wheels for survey modes, but three coronagraph concepts were identified that could give sufficient performance. After study (Spergel et al., 2015), the newly configured mission was approved by the mid-decadal survey (NRC, 2016), contingent on a \$3.2 billion cost. The coronagraph instrument (CGI) was included in the mission baseline, with a primary role as a technology demonstrator but also with a significant and capable science program.

In Phase A, the mission experienced significant cost pressure (not primarily driven by the coronagraph), and both NASA cost estimates and an independent review, the WFIRST Independent External Technical/Management/Cost Review (WIETR), identified that it was likely to exceed the \$3.2 billion cap, and also highlighted the risk that the coronagraph was underresourced for a full scientific instrument.[3] In response, NASA implemented several cost control measures on the primary mission and down-scoped the coronagraph to a pure technology demonstration, reducing the filter set to the bare minimum and eliminating any funded science program or institutional observer support. Some science may still be carried out under a "participating scientist" model as long as there is no significant additional cost.

WFIRST-CGI will provide significant risk reduction for future missions. Already, the detailed systems engineering and modeling needed to produce a flight-ready CGI design has led to rapid maturation of coronagraph concepts and identification of technology readiness issues such as deformable mirror stability and radiation damage to ultra-low-noise charge coupled devices (CCDs). Interactions between the telescope and coronagraph, such as polarization or jitter effects, are challenging and uncertain in ground simulations, and performance predictions for future missions carry modeling

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[3] See https://www.nasa.gov/sites/default/files/atoms/files/wietr_final_report_101917.pdf.

uncertainty terms that lead to challenging future-mission telescope requirements. Most importantly, operating an advanced coronagraph on exoplanetary targets in flight will lead to the development and quantification of the capabilities of existing analysis techniques. For example, techniques developed to remove correlated point spread function (PSF) noise and extract planetary spectra for ground-based coronagraphs will operate differently on space mission data, and quantifying the final noise properties of extracted spectra as a function of collected flux is crucial to determining the scope of future missions. Algorithms that combine wavefront control and PSF analysis hold great promise for extracting faint planetary signals while relaxing telescope stability requirements, but are best tested with a realistic target and in a flight environment. Given these opportunities, WFIRST-CGI's benefits are greatest when it allows flexibility for testing new approaches and retains some ability to carry out meaningful quantitative exoplanet spectroscopy, even on a very small number of targets.

> **Finding:** Flying a capable coronagraph on WFIRST will provide significant risk reduction and technological advancement for future coronagraph missions. The greatest value compared to ground testing will come from observations and analysis of actual exoplanets, and in a flexible architecture that will allow testing of newly developed algorithms and methods.

Even after the cost reductions in the coronagraph, it is still highly sensitive for imaging circumstellar dust. Simulations show that it could detect dust disks at the level of roughly 10 times solar zodiacal dust densities around nearby (<10 pc) Sun-like stars, which represents a significant subset of the targets for future large strategic missions. This sensitivity level would significantly surpass that of the Large Binocular Telescope Interferometer (LBTI) Hunt for Observable Signatures of Terrestrial Systems (HOSTS) campaign (Ertel et al., 2018), also directly measuring visible-wavelength scattered light, reducing the uncertainty of extrasolar zodiacal light impacting a future planet-imaging mission.

> **Finding:** The WFIRST-Coronagraph Instrument (CGI) at current capabilities will carry out important measurements of extrasolar zodiacal dust around nearby stars at greater sensitivity than any other current or near-term facility.

WFIRST Starshade

Although the WFIRST telescope aperture and spacecraft design make it a challenging mission for an internal coronagraph, a starshade occulter could provide it with a capable exoplanet imaging capability. Occulters have high throughput (even with an obscured aperture) and can achieve a relatively small IWA (limited by occulter size and cost rather than telescope size) with good flux ratio sensitivity. The long retargeting time scales of a starshade work well with a general astrophysics mission such as WFIRST, and the WFIRST starshade mission has an order of magnitude higher effective throughput and hence higher science reach than the WFIRST-CGI.

A starshade "rendezvous" mission would combine the existing WFIRST instrument package with a separately launched starshade spacecraft. This was studied as one starshade mode by a NASA-led science definition team and the mission concept is being updated in preparation for the decadal survey.[4] This would be a probe-class mission, for which no NASA Astrophysics Division funding line currently exists. It would therefore have to be selected as either a strategic mission by the 2020 Decadal Survey, or selected as part of a competed probe-class mission line established by the 2020 Decadal Survey. Either way, if it were to proceed, it would almost certainly launch in the latter half of the baseline WFIRST mission. The probe study found that WFIRST with a starshade would be capable of spectroscopically characterizing a large sample of known giant extrasolar planets at high SNR, mapping extrasolar zodiacal dust, and exploring nearby stars for smaller planets. It has some potential to detect (but not characterize) Earth-size habitable zone planets, as well, but only around a small number of the very nearest bright stars.

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[4] See https://exoplanets.nasa.gov/internal_resources/788/.

A final evaluation of its scientific capability will be available at the end of the mission study in early 2019.

Large Strategic Coronagraph Missions

In preparation for the 2020 Decadal Survey, NASA is funding two design studies for large strategic missions with significant capability to directly image exoplanets in reflected light. The Habitable Exoplanet (HabEx) observatory is designed to prioritize such exoplanet science, achieving Earth-analogue sensitivity through careful optimization of the telescope and instrument, while the Large Ultraviolet Optical Infrared (LUVOIR) telescope is a general-purpose astrophysics mission with similar capabilities in a larger and more flexible architecture. Both designs are currently being optimized, and both studies will likely include both a larger and a smaller design. They can be thought of as points on a continuum of missions, with the ultimate trade between cost, complexity, exoplanet characterization capability, and other astrophysical capabilities to be made by the 2020 Decadal Survey. The scale of such a mission is ultimately a question for the next decadal survey, which will balance the cost and capabilities against other opportunities. A 4 m class mission probing ~50 effective habitable zones would yield ~10 habitable zone terrestrial planets and begin to explore the diversity of such worlds in atmospheric properties composition and provide the first meaningful measurement or upper limit on the occurrence rate of potentially habitable worlds. Even if planet occurrence rates are lower than expected, it would have a high probability of at least one characterizable planet. A 10-15 m extremely large mission would of course produce a correspondingly larger sample: with ~50 worlds, rare classes of planets could be seen, and statistical trends in planet properties with the other properties of their host systems (such as stellar age or the presence of giant planets) would begin to emerge. The notional HabEx and LUVOIR represent points in a continuum of exoplanet science. All large, strategic, direct imaging mission architectures are capable of transformative science in the integrated study of planetary systems.

HabEx

The HabEx concept prioritizes exoplanet detection science above all other science. To maximize coronagraph performance, its baseline architecture uses a 4 m monolithic telescope with an off-axis secondary mirror. It is capable of operations from 120 to 1800 nm, although exoplanet observations for typical targets would be in the 300-1000 nm range. In addition to UV/Vis general astrophysics instruments, there would be an exoplanet imager and integral field spectrograph. An internal coronagraph would allow an inner working angle of ~60 mas at 500 nm and be used primarily for discovery and orbit determination; a starshade would allow a similar IWA at all wavelengths shorter than 1200 nm and be used for high-sensitivity spectroscopic follow-up of planetary systems. If equipped with a starshade, HabEx could also have a large OWA, potentially enabling a more complete assay of the outer parts of planetary systems than an internal coronagraph alone.

LUVOIR

The LUVOIR design study is exploring an extremely large and capable general-purpose observatory, a true successor to HST and JWST. The current study covers two architectures, with an 8 m and 15 m diameter, with the 15 m architecture being on axis, whereas the 8 m architecture is off axis. The full suite of instruments operates from 100 to 2400 nm (although performance beyond 1800 nm is limited by the warm telescope), with coronagraphic operations primarily from 200 to 1800 nm. The obscured aperture of the 15 m architecture somewhat degrades coronagraph performance (see Figure 4.5), but this is offset by the larger telescope diameter, and the mission is capable of detecting and characterizing Earth-analogue planets to considerable distances.

OST

The Origin Space Telescope (OST)'s greatest exoplanet science capabilities are in the area of protoplanetary disk characterization and transit spectroscopy, which are discussed in other subsections of this chapter. The OST study is also considering a secondary coronagraphic mode, but this would be a relatively low performance mid-infrared coronagraph; improved from JWST but still capable primarily of studying young giant planets, because the IWA of a MIR traditional monolithic (noninterferometric) telescope such as OST would be larger by a factor of roughly λ/D, or a factor of roughly 10 for observations at 10 microns versus observations at 1 micron for the same diameter telescope.

Probe-Class Missions

The scaling of inner working angle with telescope diameter sets a minimum practical size for a coronagraph mission capable of studying habitable-zone Earth-size planets, while the sheer faintness of Earth analogues (which have apparent magnitudes of roughly V = 30 for systems at 10 pc) renders spectroscopic characterization challenging with moderate-size telescopes even with a starshade (which generally has higher throughput). However, absolute flux ratio floors are somewhat independent of telescope diameter, so small telescopes can still detect large planets outside the habitable zone or around very nearby stars, and characterize the brighter (giant) planets. Coronagraph missions with diameters of 1-2 m can have significant science reach for studying giant planets in wider (1-10 AU) orbits, as well as some ability to study super-Earth or mini-Neptune size planets, which are known to be very common (see Chapter 2).

NASA funded two studies of Probe-class missions, Exoplanet Direct Imaging: Coronagraph (Exo-C; a 1.4 m telescope with an internal coronagraph) and Exoplanet Direct Imaging: Starshade (Exo-S; a low-cost 1.1 m telescope paired with a starshade, or a larger starshade to operate with WFIRST). Both showed significant science reach, capable of spectroscopically characterizing 10-20 known giant planets at high signal-to-noise ratio, discovering 1-4 R_E planets around a significant sample of stars, mapping and detecting circumstellar dust around young and mature stars, and (potentially) finding Earth-size planets around the very nearest stars. Both are significantly more capable than the current WFIRST-CGI implementation. These studies had a $1 billion cost cap; expanding slightly beyond that cost cap would further enhance their science capabilities. If WFIRST does not fly with a coronagraph or starshade, such missions would also provide risk reduction for a future large mission, while developing a scientific community and analysis techniques that will lay the groundwork for the scientific operation of a large coronagraph.

> **Finding:** A probe-class coronagraph or stand-alone starshade mission has significant scientific capability for studying giant planets and would provide risk reduction for a future large mission.

Technology Gaps for Space-Based Imaging Missions

For the past few years, the NASA Exoplanet Exploration Program (ExEP) has been maintaining a list of technology gaps pertaining to possible exoplanet missions, working with the community to identify, track, and prioritize these gaps and, ultimately, close them via investment in technology development projects. The technology gaps are summarized in ExEP's annually updated Technology List and captured in detail in their Technology Plan Appendix.[5] A possible roadmap to advance these technologies is described in Crill and Siegler (2017) and Crill et al. (2018, white paper).

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[5] See https://exoplanets.nasa.gov/exep/technology/gap-lists/ and https://exoplanets.nasa.gov/exep/technology/technology-overview.

Internal Coronagraphs

Internal coronagraph technologies include coronagraphic masks, deformable mirrors, low-order wavefront sensors, and wavefront control algorithms. The requirement for imaging an Earth-like planet around a Sun-like star is 1-2 orders of magnitude more demanding than WFIRST's expected performance. The latter is limited by a combination of suboptimal aperture shape geometry, which is heavily obscured, and pointing specifications. Internal coronagraph performance demonstrations with clear off-axis apertures (no central obscuration) are close to achieving the 10^{-10} contrast goal in the lab. A raw contrast of 10^{-10} is the baseline requirement for HabEx architecture A (off-axis monolith).

Some of the alternative architectures for HabEx, on the other hand, are composed of segmented apertures, which also encompass all the architectures that are being considered by LUVOIR. The latter may also be on axis and so will have a central obscuration. Several efforts are under way to address the challenge of high-contrast coronagraphy on segmented and obscured telescopes, leveraging the technology and tools developed for the WFIRST-CGI. In particular, the ExEP chartered the Segmented Coronagraph Design and Analysis (SCDA) in 2016. The study, led by the Jet Propulsion Laboratory (JPL), has gathered experts in all available coronagraph technologies.

To address the overall maturity of coronagraphs for future missions, ExEP has established the Decadal Survey Testbed (DST), intended to validate the performance of advanced coronagraphs suitable for HabEx and LUVOIR. The most promising coronagraph designs will be fabricated and tested in air and then in the DST in 2019. By 2020 the ExEP should know how well each coronagraph design would work with all architectures considered for future exoplanet missions.

Coronagraph and wavefront control technologies are critical to future direct imaging missions. However, due to the extremely low rate of photons detected from distant exoplanets, performing spectroscopy at a sufficient SNR will require the contrast to be maintained for integration periods lasting hundreds of hours. In the case of coronagraphy, this is expected to translate to sensing and controlling wavefront errors typically between 10-100 pm RMS for a telescope and instrument system (Nemati et al., 2017). While instrument-level lab demonstrations to date are within factor of a few of this requirement, this is 1 to 2 orders of magnitude more demanding than the performance of current and upcoming space telescopes.

This level of extreme wavefront stability needs to be maintained, as the space observatory and its coronagraph experience typical environmental disturbances during operation, such as dynamic jitter and thermal drifts. Large mirrors, both monolithic and segmented, will be challenged by the need to achieve a stable back-structure, and segmented mirrors will need to maintain a large number of individual segments as a single paraboloid. Due to these tight stability requirements, coronagraphs can no longer be designed as separate payload instruments and, instead, need to be designed along with the observatory as a single system. Ongoing analyses by the HabEx and LUVOIR study design teams are determining the best approach to these challenges for space-based telescopes of a range of sizes. Their work, and the assessment thereof, will determine the likelihood that these telescope systems can meet these very demanding wavefront error stability requirements.

Starshades

Starshade technology is currently being advanced under a single ExEP technology development activity whose objective is to advance five key technologies to technology readiness level (TRL) 5. WFIRST is being used as a reference mission for the design and engineering work (a starshade, however, is not baselined for WFIRST). While a starshade's optical performance can never be demonstrated at full scale on the ground, a preliminary assessment (Seager et al., 2015) has developed design models with error budgets predicting better than 10^{-10} contrast.[6] A subscale validation demonstration has already achieved 4.6×10^{-8} starlight suppression at flight Fresnel numbers, and is expected to demonstrate the 10^{-9}

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[6] See https://exoplanets.nasa.gov/exep/studies/probe-scale-stdt/.

starlight suppression goal in 2018. However, to test at these regimes and operate within a practically sized testbed, the demonstration is being conducted with only a 25 mm starshade. (Note that the testbed is already 77 m long; testing larger size starshades requires very long testbeds, as the required separation between the starshade and "telescope" increase by the square of the starshade radius). Hence, the confidence with which these subscale starshade demonstrations represent full-scale performance will depend on their ability to validate their performance models. Although scalar diffraction theory predicts optical performance to be independent of scale, wavelength-scale features in small starshades could introduce additional effects, and their final performance remains uncertain. Additional suppression demonstrations are planned to be completed by CY20 at different wavelengths, starshade sizes, and a range of key perturbations to demonstrate the reliability of the models.

Another key starshade technology that is currently being advanced is the reduction of the scattering of sunlight off the starshade's petal edges. Materials that are sufficiently thin, have low reflectivity, and are suitable for stowage, are being investigated as "optical edges." Amorphous metals are a promising candidate and are currently being tested. Unlike other large structural deployments, the starshade requires precise and stable positioning of a 30 m structure (or larger) to better than 1 mm. A half-scale or larger prototype is currently being planned, in order to demonstrate that it meets deployment tolerances.

In the case of a starshade-only mission, telescope stability requirements are significantly looser and do not exceed the state-of-the-art. Solutions for sensing and alignment control between the two spacecrafts have been developed, and subscale demonstrations are being conducted in the lab. Thus, the technology development for missions that utilize starshades falls primarily on the starshade itself, and not on the optical telescope assembly.

Low-Noise Detectors for Space-Based Applications

The low flux from small exoplanets requires a detector with read noise and spurious photon count rate as close to zero as possible, which also maintains adequate performance for many years in the space environment (Rauscher et al., 2016). The state-of-the-art is dependent on the wavelength band, but detectors need to perform at or near the photon counting limit from the UV through the NIR for current mission concepts. Across this wavelength range, the state-of-the-art detectors are semiconductor-based devices. WFIRST's electron multiplying charge coupled device (EMCCD) detectors have achieved adequate noise performance in the visible band, although longer lifetime in the space radiation environment, and higher quantum efficiency at long wavelengths, are needed. Similar EMCCD devices, with delta doping, may already have adequate performance in the near-UV. HAWAII4 HgCdTe detectors with multiple-readout noise levels of a few electrons are the state-of-the-art in the NIR, but photon-counting NIR detectors may also be required. Avalanche photodiode arrays are a promising approach but currently at low TRL. Energy-resolving superconducting sensors, such as microwave kinetic inductance detectors (MKIDs), are also a potential option, but at low TRLs for spaceflight. JWST/Mid-Infrared Instrument (MIRI)'s detectors are expected to establish the state-of-the-art in MIR detection sensitivity, and future MIR direct imaging is likely to require detectors that exceed it. It is likely that the detection sensitivity gap can be closed in the next decade, as a range of choices are close to meeting the requirements.

Development Beyond the New Worlds Vision

Practically, the vision laid out above for space-based missions focuses on UV to near-infrared characterization of planets at low spectral resolution, primarily enabling the measurement of (for terrestrial planets) Rayleigh scattering, oxygen, ozone, water vapor, and potentially methane and carbon dioxide. Significant additional information about planetary atmospheres (see Chapter 3) is available at longer wavelengths or higher spectral resolutions. However, both are technically challenging; in simple λ/D scaling, a thermal-IR (10 micron) telescope would have to be 10-20 times larger than a visible-light optimized telescope to achieve the same diffraction limit. In practical terms, this would likely have to be implemented as either a sparse aperture or a multispacecraft interferometer such as the Terrestrial Planet Finder Interferometer (TPF-I) or Darwin concepts. Moderate- to high-resolution spectroscopy of all but the nearest and brightest planets similarly requires larger collecting areas. Ultimately, the details of such future characterization will be informed by the discoveries that will be made over the next decade. While the core path flows to the large strategic exoplanet imaging mission discussed in earlier sections, it is important to retain the flexibility in planning, implementing and operating the missions of the next two decades to allow them to respond to the evolution of the scientific and technological landscape. It is also important to develop the technology that will be needed for the successor missions 20 years from now.

> **Finding:** Technology development support in the next decade for future characterization concepts such as mid-infrared (MIR) interferometers or very large/sparse apertures will be needed to enable strategic exoplanet missions beyond 2040.

OPPORTUNITIES TO CHARACTERIZE PLANETS THROUGH TRANSITS

The transit technique has now eclipsed RVs in the number and dynamic range of detected exoplanets. NASA's Kepler mission was a resounding success, and has revealed the demographics of planets on close-in orbits as well as discovering numerous exoplanets orbiting in the liquid water habitable zones of their host stars. Building on these successes, the next decade of transiting exoplanet science involves new missions to provide a more complete census of transiting planets orbiting bright stars, and a push toward a statistical census of Earth-size habitable zone planets orbiting Sun-like stars. These missions will provide many of the targets for atmospheric characterization efforts, which rely on high SNR to detect the minute signature of atmospheric absorption, emission, or scattering in a differential sense against the bright background of a much larger host star. Below, the committee outlines first the upcoming transit survey missions and how they will alter the landscape of the known transiting exoplanet population toward fulfilling the goals of the Exoplanet Science Strategy. It then presents the next decade and beyond of observational efforts to characterize the atmospheres of transiting exoplanets.

Planet Discoveries Through Transits

Transiting Exoplanet Survey Satellite (TESS)

NASA's TESS mission launched successfully in April 2018 and will shortly begin its near-all-sky survey for transiting planets (Ricker et al., 2015). TESS will mainly be sensitive to close-in planets and will find approximately 2000 planets with radii less than Neptune (see Figure 4.6; Barclay et al., 2018). This will give the opportunity to explore the statistics of the mass-radius diagram (in concert with the radial velocity technique; see the section "Exoplanet Masses," later in this chapter) and provide essential targets for large atmospheric studies in the near term with JWST, and the longer term with the Atmospheric Remote-Sensing Exoplanet Large-Survey (ARIEL; see the section "Atmospheric Characterization Through Transit Spectroscopy," earlier in this chapter, and Tinetti et al., 2017) and the GSMTs. TESS will also find terrestrial planets around M dwarfs that will be key targets for studies of temperate terrestrial planets, with JWST and the GSMTs playing a key role. An extended TESS mission could do important work maintaining precise ephemerides for follow-up observations, discovering longer period planets, or covering the portions of the sky omitted in the original survey (Huang et al., 2018).

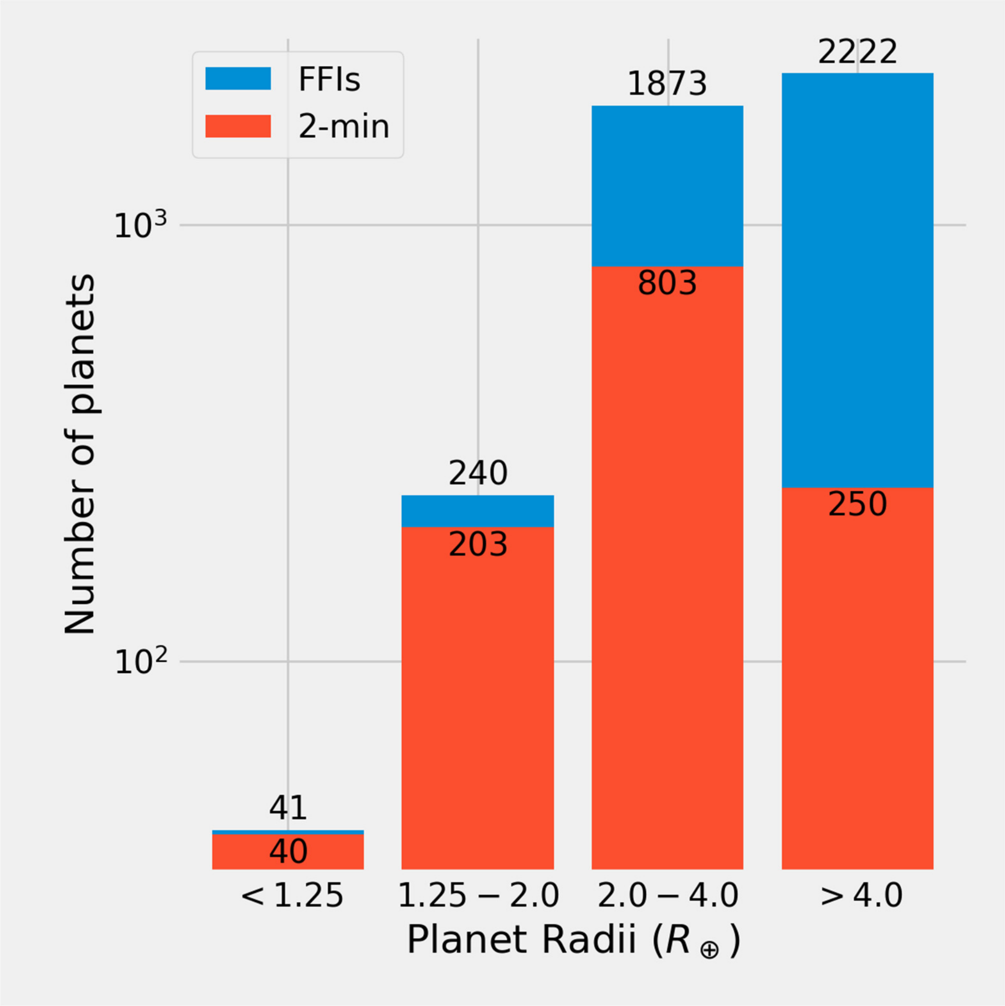

FIGURE 4.6 TESS is predicted to find approximately 2000 exoplanets smaller than 4 R_E, many of which will be good targets for follow-up mass measurements using radial velocity techniques, and follow-up atmospheric studies with JWST, ARIEL, and the GSMTs. SOURCE: Barclay et al. (2018).

Ground-Based Photometry

In the era of large space-based transit surveys, ground-based photometric observations of transiting planets and their host stars have a continued role to play in several senses, as follows:

- Ground-based surveys such as MEarth and Transiting Planets and Planetesimals Small Telescope (TRAPPIST)/Search for Habitable Planets Eclipsing Ultra-Cool Stars (SPECULOOS) are designed for planet detection in regimes of parameter space that provide unique sensitivity from the ground and can detect habitable zone planets orbiting the smallest stars, which are typically too faint for TESS.
- Ground-based follow-up to TESS (and Planetary Transits and Oscillations of Stars [PLATO]; see the next section) candidates will be necessary for vetting and confirming candidate exoplanets by ruling out systems of blended stars. This would include high-resolution imaging to spatially resolve multistar systems (or chance alignments), which are expected to be prevalent in TESS data due to the large pixel size; and multiband transit photometry to search for color dependencies in transit depth that are indicative of stellar blends.

- Long-term monitoring of transiting systems, possible only from the ground, will enable the search for additional planets in systems with one or more known close-in planets. Such monitoring can also provide ephemeris maintenance that is necessary to accommodate future atmospheric characterization follow-up studies.

The latter two points in this list would benefit from a coordinated network of ground-based telescopes with broad sky coverage purposed with monitoring transiting exoplanet hosts and following up on exoplanet candidates. Existing examples of such networks include the Las Cumbres Observatory Global Telescope (LCOGT)[7] and the Kilodegree Extremely Little Telescope Follow-Up Network (KELT-FUN; Collins et al., 2018).

Planetary Transits and Oscillations of Stars (PLATO) Mission

The European PLATO mission is a dedicated transit survey scheduled for launch in 2026 to an L2 halo orbit.[8] The mission design consists of a 0.59 m telescope with 24 cameras, with a total sky coverage of up to 50 percent, and a nominal mission duration of 4 years (with consumables lasting up to 8 years). Its observing strategy is being designed to back a science goal of detecting Earth-size habitable zone planets orbiting Sun-like stars. All primary science targets with $V < 11$ would also be characterized asteroseismologically, thus providing precise radii and ages for the host stars and their planet candidates. An accompanying ground-based RV follow-up campaign is also envisaged to measure planetary masses. The exact observing strategy is still being developed, with trade-offs being considered between sky coverage and duration of observations on individual fields.

The unique transiting planet science accomplished by PLATO will include improving knowledge of the occurrence rate of Earth-like planets orbiting Sun-like stars over that provided by Kepler; delivering a sample of habitable-zone terrestrial planets orbiting bright G and K stars for future atmospheric characterization with transit or direct imaging techniques; and mapping out the evolution of planet occurrence rates and properties as a function of age, by providing precise host star dating via asteroseismology.

Atmospheric Characterization Through Transit Spectroscopy

To date, the characterization of exoplanet atmospheres has occurred primarily through transit techniques (transit and secondary eclipse spectroscopy, and phase curves, which can capture both the transit and secondary eclipse). Atmospheric characterization efforts have therefore been focused on the population of close-in transiting exoplanets with large planet-star radius ratios. While large space-based direct imaging missions are currently being conceived of that would obtain spectra of terrestrial and gas giant planets at wider separations, transit spectroscopy techniques will remain the primary mode for atmospheric characterization over the next decade and beyond.

James Webb Space Telescope (JWST) Mission

JWST provides photometric and spectroscopic wavelength coverage from 0.6-28 microns (see Figure 4.7). JWST will provide high-precision spectroscopic characterization of transiting exoplanets across the near- and mid-IR, which can be used to investigate many intriguing science questions that could only previously be addressed in a limited manner by ground-based instruments, HST, and Spitzer.

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[7] For additional information on LCOGT, see https://lco.global/.

[8] For additional information on PLATO, see sci.esa.int/plato/59252-plato-definition-study-report-red-book/.

For example, JWST's wavelength coverage allows it to probe many spectroscopically interesting molecules including major oxygen-, carbon-, and nitrogen-bearing species. This capability will allow for accurate measurements of atmospheric metallicities and elemental abundance ratios (e.g., C/O) as a tracer of planet formation and evolution, and will provide a window into nonequilibrium chemical processes in exoplanet atmospheres. JWST will also yield access to smaller and cooler planets than can be targeted with HST and Spitzer due to its larger aperture and longer wavelength coverage.

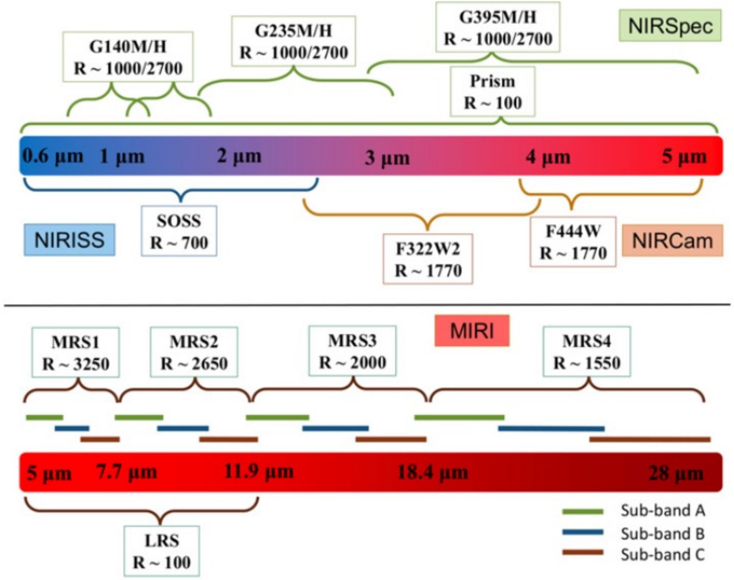

FIGURE 4.7 Overview of JWST's spectroscopic capabilities. The combination of JWST's broad wavelength coverage, high spectral resolution, and large collecting area will yield a transformative step for exoplanet atmosphere studies. SOURCE: Stevenson et al. (2016).

Ideal targets for atmospheric characterization with JWST are planets orbiting bright host stars. Hot giant planets are straightforward atmospheric targets for JWST, and in many cases a single transit or eclipse will return a high SNR exoplanet spectrum (Figure 4.8). Warm Neptune- and sub-Neptune-size planets orbiting smaller stars are also high-quality JWST targets. Archetype objects in this class include GJ 436b and GJ 1214b, and it is expected that TESS will discover on order of 100 additional similar-size planets from which additional JWST targets will be drawn (Kempton et al., 2018). Temperate terrestrial planets remain a significant challenge for JWST; for Sun-like stars such planets will remain out of reach, and for M dwarfs studies are envisioned but will require many transits or eclipses to build up a spectrum at moderate SNR (Morley et al., 2017). Nevertheless, JWST should make significant progress toward determining if terrestrial planets orbiting late-type stars can retain atmospheres.

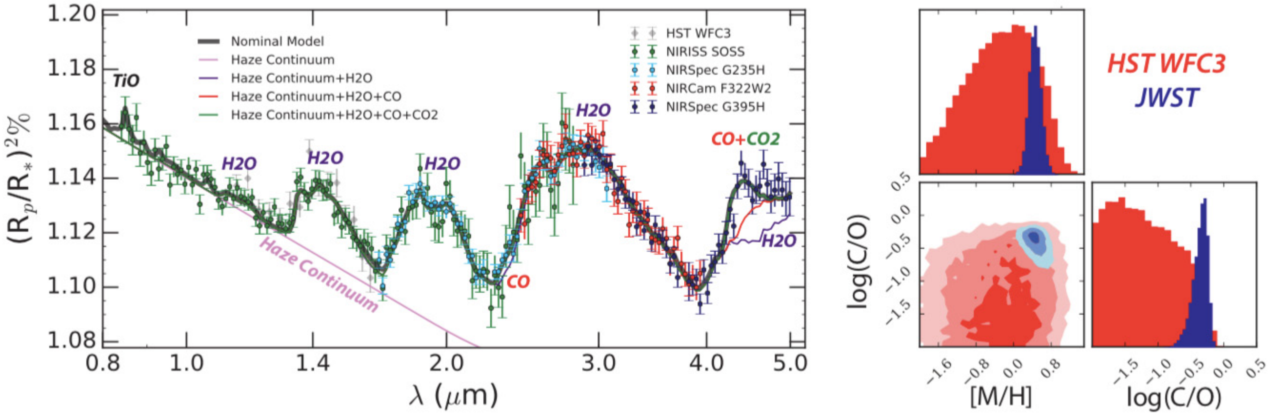

FIGURE 4.8 Example of simulated JWST transmission spectrum of a hot Jupiter (WASP-79b, left panel) and derived composition constraints (right panel). JWST's improved wavelength coverage, spectral resolution, and sensitivity will yield significantly better constraints on the properties of exoplanet atmospheres compared to existing facilities. SOURCE: Bean et al. (2018).

The exoplanet community has the ambition to characterize the atmospheres of a large number of transiting planets to reveal trends with planet mass, size, level of irradiation, and host star properties, which should inform planetary formation and evolution, and atmospheric physics and chemistry (Chapter 3). There are several challenges to accomplishing this goal. First, with a limited lifetime shared-resource facility there is a trade-off between characterizing many easy-to-observe hot giant planets versus using substantial observing time to perform detailed characterization of a much smaller number of terrestrial exoplanets. Second, there is the issue of the time allocation process itself. It is unknown what fraction of JWST time will ultimately go to exoplanet investigations, but if the history with HST provides some guidance, that number might fall around 20 percent.

The JWST launch delay means that most TESS-discovered planets will be in hand prior to the commencement of regular JWST science operations. With hundreds of high-quality atmospheric characterization targets to choose from, multiple choices of observing modes and wavelength coverage, and many competing research groups that have spent years eagerly awaiting the launch of JWST; one might expect an onslaught of observing proposals in the early cycles of the JWST mission with no clear overarching science vision. This leads to a third challenge, which is one of community organization. It would have a powerful impact if the transiting exoplanet community could come together behind a shared strategic vision of atmospheric characterization science with JWST. The resounding success of the Early Release Science (ERS) program with JWST has shown that such an effort is possible among exoplanet researchers (Bean et al., 2018). The "Transiting Exoplanet Community Early Release Science Program" was the top ranked proposal in the competitive ERS selection process, and it garnered the largest time allocation of any of the selected proposals. The proposal team consisted of 61 investigators and 43 collaborators, representing multiple individual (and competing) research groups.

The Exoplanet Science Strategy outlined in this report provides some of the framework for a shared strategic vision in atmospheric characterization with JWST. For the first time JWST will bring exoplanet atmospheric characterization efforts from a regime of limited observations to one of high-fidelity spectroscopic investigations of a comparative sample (Cowan et al., 2015). To take advantage of this opportunity, JWST should undertake a strategic and systematic survey of exoplanet atmospheres that will benefit the entire research community and guide future observing strategies for years, if not decades (Cowan et al., 2015). While a mechanism is not currently in place for key science programs with JWST, it would behoove the exoplanet community to perform such a survey as early in the mission as possible, to inform future science strategies both in later JWST cycles and in the development of next-generation facilities.

> **Recommendation: NASA should create a mechanism for community-driven legacy surveys of exoplanet atmospheres early in the JWST mission.**

Future Large Missions for Transit Spectroscopy Beyond JWST

Despite JWST's substantial power for transiting planet observations, the committee concludes that some significant science questions will remain in this topic after the mission is completed, particularly because JWST will not have sufficient collecting area to probe a large number of habitable planets and also because it will not cover all the wavelengths of interest. The OST, LUVOIR, HabEx, and Lynx mission concepts would all probe exoplanet atmospheres in new ways given their unique wavelength coverage compared to JWST, while an optical or infrared mission with substantially larger collecting area (e.g., LUVOIR or a large version of OST) would expand the number of potentially habitable planets that can be studied.

The characterization of a large number of potentially habitable planets will likely be out of reach for JWST (Louie et al., 2018; Batalha et al., 2018). The expected outcome is that JWST will at best be able to detect molecules for only a handful of especially favorable potentially habitable planets (i.e., planets around mid to late M dwarfs within 10 pc). Among the current mission concepts being studied in preparation for the decadal survey, OST and LUVOIR could make further progress on the topic of terrestrial planet habitability using transit techniques.

OST is being designed specifically to extend JWST transmission and emission spectroscopy science with observations at wavelengths between 5 and 25 microns in a single pointing. The spectral coverage and sensitivity of OST will enable the detection of molecules that govern planetary climate, such as carbon dioxide and water, as well as the exciting biosignature combination of ozone and methane. Although JWST will have spectroscopic capability for wavelengths longer than 12 microns (see Figure 4.7), it is currently anticipated that these will not perform well for transit spectroscopy, because the Medium Resolution Spectroscopy (MRS) modes of MIRI are fed with an integral field unit that has relatively small entrance apertures. Thus, it is expected that classical transit spectroscopy will be not be possible with these modes due to uncorrectable slit losses (but see Snellen et al., 2017). OST is expected to be capable of transit spectroscopy at longer wavelengths ($\lambda > 12$ microns) compared to JWST. This opens up the possibility of seeing past aerosol scattering and determining aerosol compositions through the detection of vibrational transitions. Nevertheless, the committee notes that Earth's thermal emission peaks at 10 microns and the spectra of temperate terrestrial planets drop precipitously beyond 18 microns due to the decline of thermal blackbody emission and strong water absorption. JWST does have photometric capabilities that extend beyond the MIRI Low Resolution Spectrometer (LRS) cutoff, and since observations of potentially habitable planets at these wavelengths will likely be limited by photon counting noise, OST spectroscopy would offer only a modest improvement over JWST in this area.

Unlike JWST, OST is designed from conception to have low levels of systematic noise for time-series observations. However, the noise floor of JWST is unknown and the success of the community in using HST and Spitzer, which are much less optimized for transit observations than JWST, leads the committee to be optimistic about its expected performance. Ultimately, the limiting factor for transit spectroscopy of potentially habitable planets will be the number of stellar photons that can be collected, and the committee finds that JWST-size and smaller telescopes do not have sufficient light gathering capabilities to study a large number of such objects. Therefore, the committee concludes that OST would need a much larger aperture to yield a transformative advance over JWST unless it is found that JWST's reach is severely limited by time-series systematics.

LUVOIR would also advance transiting planet science in the post-JWST era. LUVOIR would reopen the UV and optical wavelength range ($0.1 < \lambda < 0.6$ microns) for transiting planet observations that will close once HST is no longer operational, and it would maintain optical to near-infrared ($0.6 < \lambda < 2.5$ microns) capability once the JWST mission ends. The short wavelength range is important for exploring planetary mass loss and characterizing aerosol scattering, and a substantial number of gas phase absorbers for potentially habitable planets will also be accessible in the optical and near-infrared, including carbon dioxide, water, and the biosignature combination of molecular oxygen, ozone, and methane. The addition of a high-resolution optical or infrared spectrograph on LUVOIR would yield a substantial advance for transit observations using the cross correlation technique because of the absence of contaminating telluric lines. Similar to OST, LUVOIR's exact advantages compared to JWST beyond its unique bandpass and potential for high spectral resolution will depend on the differences in collecting areas of the telescopes and JWST's time-series systematics, the latter of which will not be ascertained until the mission becomes operational.

> **Finding:** The combination of transiting planet detection with TESS, mass measurements with radial velocities, and atmospheric characterization with JWST will be transformative for understanding the nature and origins of close in planets. Future space missions with broader wavelength coverage, a larger collecting area, or reduced instrumental noise compared to JWST would have greater reach to potentially habitable planets.

Atmospheric Remote-Sensing Exoplanet Large-Survey (ARIEL) Mission

The European ARIEL[9] mission is a dedicated transit spectroscopy experiment planned for launch in 2028. ARIEL will comprise a 1 m-equivalent telescope equipped with an infrared spectrograph, giving spectral coverage from 2.0 to 7.8 microns in a single pointing. ARIEL will carry out a nominal 4 year mission at Lagrange 2 point (L2), with a possible extension to 6 years.

ARIEL's goals are to characterize the atmospheres of approximately 1000 planets in order to search for trends that can be revealed only statistically. By comparison, JWST is expected to characterize the atmospheres of approximately 100 exoplanets, but at significantly higher precision (Cowan et al., 2015). The trends that ARIEL will characterize include the relationship between atmospheric metallicity and planet mass, the distribution of atmospheric carbon-to-oxygen ratios, and the variations of energy transport and thermal structure with irradiation level. Ultimately, ARIEL provides a wide and shallow survey that complements JWST's more narrow and deep observations. Furthermore, ARIEL's capability to observe a large number of sub-Neptune to giant planets would allow JWST to focus on the smaller and cooler planets that it is uniquely capable of studying.

NASA is currently studying the possibility of contributing to the ARIEL mission by providing fine guidance sensors (FGSs) for the required precise pointing control and as auxiliary science instruments (the Contribution to ARIEL Spectroscopy of Exoplanets [CASE] mission concept). The FGSs would add spectrophotometric wavelength coverage from 0.55 to 1.90 microns, which would provide information on the albedos of planets and the presence of aerosols. U.S. scientists would benefit from the CASE mission by participating in the planning, execution, and exploitation of the ARIEL survey.

> **Finding:** By conducting a statistical survey of exoplanet atmospheres, the European ARIEL mission will provide broader context for more focused JWST observations. The U.S. exoplanet community would benefit from participation in ARIEL.

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[9] For more information on ARIEL, see http://sci.esa.int/ariel/ and https://ariel-spacemission.eu/.

Giant Segmented Mirror Telescopes

Transit spectroscopy observations are challenging from the ground because of the inherent variability of Earth's atmosphere, its opaqueness at many infrared wavelengths, the thermal emission at mid-infrared wavelengths, and the lack of continuous observability of the night sky at most locations on Earth imposed by its daily rotation. However, the photon collecting power of the upcoming GSMTs will be a factor of 15-36 larger than that of JWST. Ground-based telescopes offer a more stable instrument environment at lower cost than space telescopes, more flexible instrument setups, and the potential to deploy new instruments on a short time scale. Therefore, ground-based observatories have certain advantages over space-based platforms, despite the challenge of observing on Earth and, in particular, through Earth's atmosphere.

Accurate calibration of transmission or secondary eclipse spectra can be obtained by simultaneously observing a nearby reference star (Bean et al., 2010), but this is unlikely to rival future space-based observations, except for very faint targets. A particularly powerful technique involves High-Dispersion Spectroscopy (HDS) using spectrographs with resolving powers of R > 25,000 (Figure 4.9; Snellen et al., 2010). While this technique does not preserve spectroscopic broadband features, it allows accurate instantaneous calibration of Earth's atmosphere and measures the contrasts of atomic and molecular lines in the planet spectrum. The signal of many lines can be combined to boost the signal of a particular molecule, which is identified through cross correlation of the observed spectrum against a model planet spectrum. The technique can be used for transmission spectroscopy, but can also target the emission and reflection spectra from nontransiting planets. The change in the radial component of the orbital velocity of the planet can be used to disentangle the stellar and telluric components of the spectrum from that of the planet. This technique can further be used to constrain the orbital inclination of nontransiting planets, thereby allowing a measurement of the true mass (rather than the minimum mass) of a planet detected only by the radial velocity method.

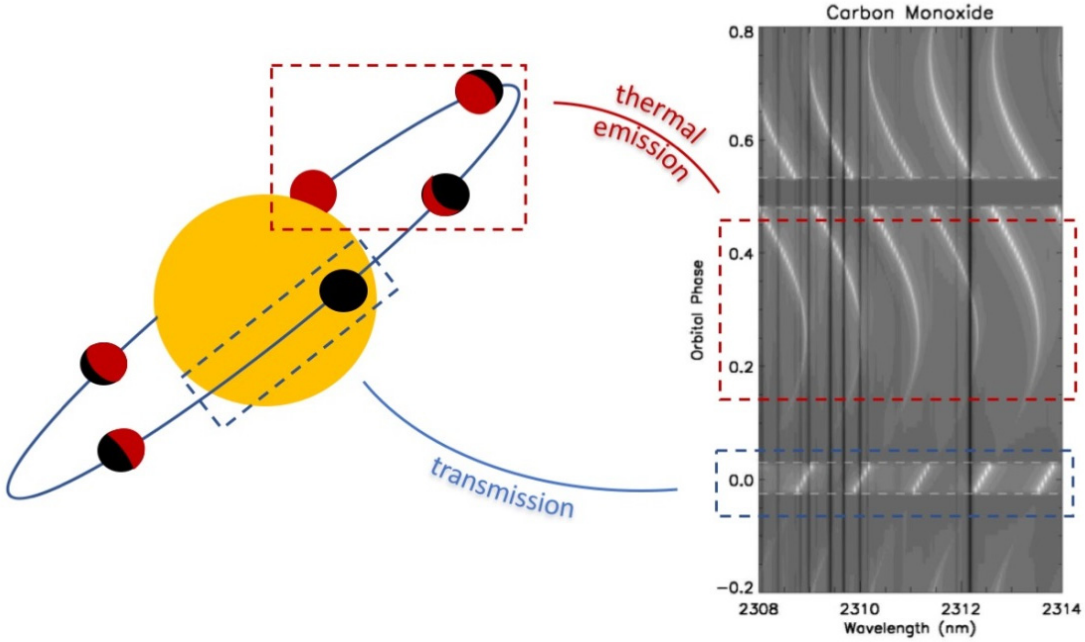

FIGURE 4.9 Illustration of the high-dispersion spectroscopy technique, targeting a planet's transmission spectrum (blue box) or thermal emission spectrum (red box), of which the latter is also sensitive to nontransiting planets and can break the orbital inclination degeneracy. The right panel shows a toy model of a planet spectrum (white lines), which exhibits a change in the radial component of the planet orbital velocity as function of phase. The telluric lines (in black; mainly from water and methane) are quasi-stationary and thus can be removed.

The GSMTs will provide a major step forward for this method. The atmospheres of rocky planets in the habitable zones of nearby M dwarfs are within reach, including the detection of carbon dioxide, methane, water, and molecular oxygen (Maiolino et al., 2013; Rodler and Lopez-Morales, 2014). More generally, the method is complementary to space-based observations in the following senses:

- The reliance on molecular transitions results in unambiguous molecular identifications.
- The sensitivity to Doppler effects means it can measure the atmospheric dynamics and spin of the planet (e.g., Snellen et al., 2010, 2014; Rauscher and Kempton, 2014).
- Lines of different oscillator strengths probe different altitudes in a planet atmosphere, providing a unique measure of the atmospheric temperature structure. For dayside emission this can be used to map the variation of the atmospheric temperature with longitude.
- The method probes atmospheres at lower pressures than low-dispersion spectroscopy, making it less affected by clouds and hazes (e.g., Kempton et al., 2014).
- The method could allow for the detection of different molecular isotopologue ratios, such as HDO/H_2O, providing unique insight in the formation history of exoplanets.

The following relevant instruments are currently envisaged for on the GSMTs: For the GMT, the Giant Magellan Telescope-Consortium Large Earth Finder (G-CLEF) will be a high-resolution, highly stable, fiber-fed visible light échelle spectrograph operating from 350 nm to 950 nm with spectral resolutions up to 120,000, and the Giant Magellan Telescope Near-Infrared Spectrograph (GMTNIRS) will cover 1-5 microns with a resolution up to 100,000. TMT could select a second-generation instrument, High-Resolution Optical Spectrometer (HROS) or Near-Infrared Echelle Spectrometer (NIRES), with high-dispersion capabilities in the optical or near infrared, respectively. On the European ELT, the Mid-Infrared E-ELT Imager and Spectrograph (METIS) will contain an R = 100,000 Integral Field Unit (IFU) for the L and M bands, and the High Resolution Imaging Spectrometer (HIRIS), an optical-near-IR high-dispersion spectrograph, is currently under study as a second-generation instrument. Novel instrument designs (e.g., Ben-Ami et al., 2018) focused on this method promise significant increases by restricting the wavelength range and boosting throughput.

> **Finding:** GMT and TMT, equipped with high-resolution optical and infrared spectrographs, will be powerful tools for studying the atmospheres of transiting and nontransiting close-in planets, and have the potential to detect molecular oxygen in temperate terrestrial planets transiting the closest and smallest stars.

EXOPLANET MASSES

As discussed in Chapter 3, knowledge of the masses of exoplanets is essential both as a diagnostic of planetary nature and as a tracer of planetary origins. Mass is the most fundamental property because of its role in planetary structure and evolution; it governs a planet's ability to form and retain an atmosphere, the strength of its dynamical interactions with other bodies, and its initial gravitational energy.

Combined with the transit technique, precise masses constrain the bulk compositions and interior structures of transiting exoplanets by yielding their densities. Kepler/K2, TESS, PLATO, and the Characterising Exoplanets Satellite (CHEOPS) missions will deliver thousands of transiting planets over the coming decade, giving the opportunity to expand studies of the planet bulk composition in terms of host star mass, age, composition, and planetary orbital separation. These missions will also identify potentially habitable planets, which are compelling targets for mass measurements in order to reveal which ones are rocky.

Masses are also needed to constrain surface gravities and atmospheric scale heights, which are key boundary conditions for interpreting spectra obtained through either the transit or direct imaging techniques. Thus, exoplanet mass measurements are important for the success of JWST, ARIEL, the GSMT exoplanet studies, and a direct imaging mission. The scientific return of direct imaging will benefit tremendously if the target masses can be determined, because direct imaging generally does not yield masses or radii, leaving such information to be extracted indirectly from spectra and with a heavy dependence on atmospheric and/or evolutionary models.

Direct imaging missions would benefit from precursor observations that not only measure planetary masses but also identify targets with planets first and map their orbits. The reason for this is that a blind direct imaging survey for planets, and Exo-Earths especially, generally spends a lot of time missing planets because they are inside the inner working angle of the instrument or are in crescent phase and are too hard to detect (Stark et al., 2014). Radial velocity measurements could predetermine the most promising candidates and, if performed contemporaneously (Savransky et al., 2009), would save observing time by targeting epochs when companions are known to be maximally separated from their stars (Crepp et al., 2016). The desire to measure the masses of giant planets beyond the snow line, to measure the masses for directly imaged giant planets, and to illuminate the formation histories of planetary systems that include directly imaged terrestrials motivates radial velocity monitoring over decades (Montet et al., 2014; Howard and Fulton, 2016).

The radial velocity technique remains the principle method for measuring planet masses because of its wide applicability. The transit timing variation (TTV) technique is useful for the subset of compact, multiplanet systems that are in or near resonance. Astrometry has not been widely used to date, but results from GAIA are eagerly anticipated.

Radial Velocities

Since the last decadal survey researchers have entered the era of extremely precise radial velocities (EPRVs), with detections of planetary signals of 1 m/s. For Sun-like stars, this corresponds to planets with masses as small as several times that of Earth, but only for orbital periods of several days. Although impressive (approximately 0.001 pixel Doppler shift recovery), this level of precision is insufficient to detect the gravitational perturbation induced by an Earth-Sun analogue.

For rocky planets in the habitable zones of mid to late M dwarfs, the RV signal is several meters per second, and a number of such measurements have been made (e.g., Anglada-Escude et al., 2016), including one transiting example (LHS1140b; Dittmann et al., 2017). A number of specialized instruments focused on discovery and mass determination for M-dwarf planets are recently commissioned or coming online in the next year (see Fischer et al., 2016; Wright and Robertson, 2017). These facilities will play an essential role in determining the density and surface gravities of the potentially habitable planets transiting the closest small stars, which will be scrutinized by JWST and the GSMTs.

Despite the efforts of many teams, the state-of-the-art in Doppler precision has experienced only marginal improvements in the last 5-10 years, reaching an apparent plateau in performance just beneath 1 m/s for bright stars (Fischer et al., 2016). Earth-mass planets in the habitable zones of Sun-like stars require an improvement in radial velocity precision to the cm/s level (Figure 4.10). This is beyond the reach of the expected performance of instruments being built today, including the high precision Doppler spectrograph under development by the NASA-NSF Exoplanet Observational Research (NN-EXPLORE) partnership (Schwab et al., 2016). Furthermore, even if spectrographs reach this internal precision, mass measurements will likely be limited by two noninstrumental effects: stellar variability and contamination from telluric lines.

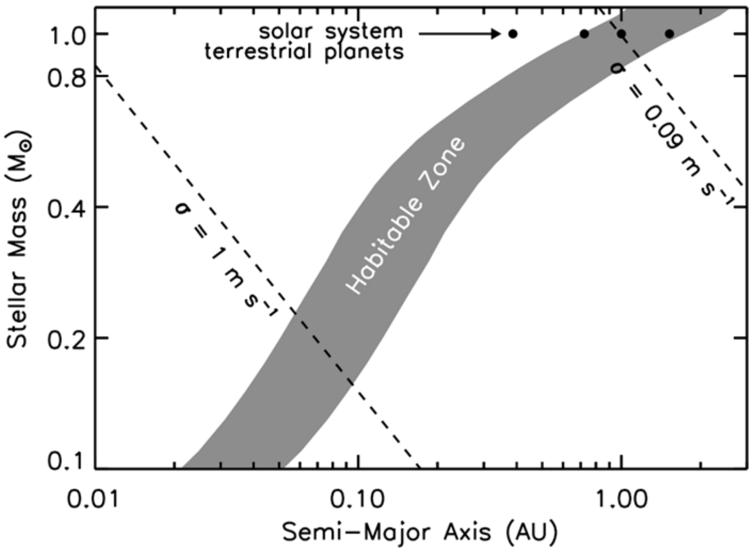

FIGURE 4.10 Radial velocity sensitivity requirements as a function of stellar mass and semimajor axis. The shaded region indicates the location of the traditional liquid water habitable zone (Selsis et al., 2007). The dashed lines show where the radial velocity semi-amplitude of a 1 M_E planet would equal either 1 or 0.09 m/s; with the stated precision it would be possible to detect a 1 M_E planet to the left of the line. Detection of Earth-mass planets in the habitable zones of Sun-like stars requires precisions of several cm/s.

Overcoming Stellar Variability

The surface of Sun-like stars are mottled by numerous effects, including convective granulation and magnetic phenomena such as spots, plage, and faculae. As these effects evolve in time, and as features rotate into and out of view on the differentially rotating surface, these inhomogeneities create spurious Doppler shifts that severely complicate the interpretation of RV time series measurements (e.g., Dumusque et al., 2014). A distinguishing factor between stellar variability and the purely translational shift caused by an orbiting planet is that surface features create changes in the detailed shapes of absorption lines, in ways that often vary with wavelength (e.g., Queloz et al., 2001). Future EPRV instruments need to therefore have sufficient spectral resolution (R > 100,000 at a minimum, and R > 200,000 ideally), spectral coverage, SNR, and observing cadence to measure, and subsequently correct for, stellar variability (Fischer et al., 2016; Davis et al., 2017).

Small telescopes (D < 4 m) will not be able to satisfy all of the above requirements since they likely cannot achieve the requisite SNR at the required dispersion in the required integration time. Moreover, measurements carried out with sufficient cadence to explicitly resolve the various time scales of stellar variability will enable separating these signals from planetary signals. For example, pressure-mode (p-mode) oscillations have a characteristic time scale of 5 minutes for the Sun (Koen et al., 2003). Current observing strategies purposefully alias the signal by targeting the nodes of pulsation time series, or they simply average over them by exposing for significantly longer than the characteristic time scale of these oscillations. Resolving this signal would enable removing it more effectively, but requires short integration times. This, coupled with the need for high SNR at high spectral resolution, motivates the use of larger aperture telescopes. Dedicated facilities should be considered, as acquiring sufficient observing time on large aperture telescopes typically proves difficult (Plavchan et al., 2014).

The standard approach of tracking stellar activity using familiar activity indicators (e.g., changes in the equivalent widths of the Ca H and K lines) has generally proven to have limited value. New methods should be developed that attempt to empirically model and correct for stellar variability in time.

Theorists studying magneto-hydrodynamics, stellar activity, stellar astrophysics, and heliophysics should work closely with EPRV survey teams to model absorption line profiles (Wright and Sigurdsson, 2018). Observing the Sun simultaneously with spatially resolved spectroscopy and in hemisphere-integrated light (e.g., Haywood et al., 2016; Dumusque et al., 2015) offers the opportunity to uniquely identify the surface features that result in apparent RV variations, and thus a path for comparing theoretical calculations to disk-integrated measurements. The goal of such work would be to identify metrics that could be used to correct the RVs for other stars. A more fundamental understanding of how stellar variability behaves in time and as a function of wavelength and stellar properties should be sought. Further, novel statistical methods employing principal component analysis and machine learning should be developed and refined to disentangle the signal of the Doppler shifts of absorption lines due to orbiting planets from the variability of absorption lines due to stars (Davis et al., 2017) or the atmosphere (see the next section). Such work may find that contemporaneous photometry is an essential input into the analysis (e.g., Haywood et al., 2014) to push down to a precision of several cm/s.

Telluric Contamination

Spectral contamination from telluric lines is a problem for EPRV measurements because their variation in strength and position over time scales ranging from minutes to seasons can lead to spurious radial velocity shifts much larger than the sought-after planetary signals. There is a growing sense in the EPRV community that small telluric lines, so-called micro-tellurics, are a limiting factor for ground-based observation. Macroscopic telluric lines are easily identified and masked in the radial velocity measurement process in the optical, although they remain a challenge for near-infrared radial velocities (Bean et al., 2010). By contrast, micro-tellurics require higher spectral resolution and SNRs to identify, and ultimately may be so prevalent that they cannot all be masked even if they could all be identified. Micro-tellurics affect between 4 and 10 percent of pixels, depending on the (variable) water content of the atmosphere at depths that matter for the requisite SNR of up to 300. New data-driven techniques are emerging that may circumvent this problem by modeling the lines directly. The higher spectral resolution instruments on larger telescopes motivated by the stellar variability problem will also help the telluric contamination issue. Measurements from space might be a final option if the telluric contamination problem cannot be solved. However, as described above, large apertures ($D > 4$ m) and significant time investment are required to solve the pernicious challenge of stellar variability, even for space-based measurements.

Instrument Stability

Sub-milli-Kelvin thermal stability and vacuum levels below $P = 10^{-6}$ Torr are needed to generate sub-meter-per-second single measurement precision (Mahadevan et al., 2014). The opto-mechanical footprint of seeing-limited spectrographs that generate $R > 100,000$ for 8-10 m class and larger telescopes are a challenge to stabilize at this level, as the beam diameter grows with the size of the telescope. Novel technological methods to calibrate instrument drift, including combinations of a Fabry-Perot etalon, laser-frequency combs, and emission lamps, have continued to advance. Using adaptive optics to inject starlight into small fibers would help keep EPRV instruments to manageable sizes. Diffraction-limited systems that use single-mode fibers show significant promise (Crass et al., 2018, white paper). The same technology could be used for high-dispersion coronagraphy of directly imaged planets (Jovanovic et al., 2018, white paper).

Rigorous Error Budgets

EPRV instruments present a complicated systems engineering challenge. Interpreting comprehensive error budgets to make informed design decisions is hindered by the fact that many sources of uncertainty have comparable values (Halverson et al., 2016). While provisional error budgets have been put together for recent instruments designed to generate sub-meter-per-second precision, these frameworks have largely not yet been validated empirically nor do they possess demonstrated predictive power. Reliable and quantitatively rigorous error budgets will be needed to move beyond the current generation of instruments that are coming online.

Collaboration

The EPRV community has historically been divided into numerous small teams that compete against one another for resources and generally do not share data, and yet it is widely recognized that properly addressing stellar variability requires more coordination and more resources than any one group of investigators can marshal. This approach is nonoptimal scientifically, tends to result in duplication of work in a field that has limited resources, and should be enhanced with a more collaborative and sustainable framework that encourages an open network of interinstrument sharing of spectra, data analysis methods, design concepts, and hardware development efforts, while at the same time protecting proprietary periods for data acquired by individual investigators.

Summary of RV Needs and the Motivation for an EPRV Initiative

The EPRV field needs an initiative that fosters community engagement and activities that promote collaboration and combines efforts and expertise for Doppler instrumentation, follow-up measurements, survey planning and execution, and data analysis techniques. Such an initiative should also strategically encourage the free exchange of ideas between the above-mentioned subdisciplines in stellar astrophysics, heliophysics, instrumentation, and statistics for overcoming the effects of stellar variability. An EPRV initiative could undertake the coordinated, sustained effort to tackle the myriad of error terms that currently limit RV precision.

Efforts to understand and address the subtle physical effects that manifest at the 1 cm/s level (10-sigma detection of Earth analogue) have thus far been attempted piece-meal by individual investigators. In addition to standard principal investigator (PI)-led programs, a comprehensive effort at the national level with serious capital investment is required to address the multifaceted problem inherent to measuring ultra-precise stellar RVs. A dedicated initiative is needed that organizes and coordinates the efforts of exoplanet researchers from diverse scientific backgrounds in hardware, software, operations, and related topics.

Rather than a brick-and-mortar institute located at a single physical address, the initiative should be a strategic virtual program that benefits from the contributions of researchers originating from different geographic regions and areas of expertise. The initiative should rely on NASA's experience in developing rigorous error budgets, performing trade studies, systematically working to solve challenging technical problems, and overseeing and managing numerous research teams under a common programmatic goal.

Although EPRVs were highlighted previously in the 2010 Decadal Survey, the resources allocated for ground-based support of Kepler, TESS, and forthcoming space missions have been insufficient (Plavchan et al., 2015). The scientific return from space transit missions will be increased dramatically if more resources are committed to these efforts before, during, and after launch. Ground-based measurements should be carried out leading up to the launch of a direct imaging space mission, irrespective of whether the coronagraph technology used involves an internal or an external occulter. Importantly, NASA has focused its precious resources on measuring the masses of discovered planets (which the committee emphasizes is an important goal), but not on the challenge of improving the current state-of-the-art of EPRV itself. Here, the committee advocates that together NASA and NSF take on the grand challenge of achieving the precision required to measure the masses of terrestrial planets orbiting Sun-like stars. The goal of the field should be to reach $\sigma = 10$ cm/s single measurement precision from the ground in the near term; ultimately, control of systematics at the level of roughly 1 cm/s is needed to study Earth/Sun analogue systems. While such measurements will likely be done from the ground, they are inextricably linked to the scientific success of the numerous current and proposed NASA missions, including Kepler/K2, TESS, and a future large imaging mission. NASA has tackled formidable technology challenges in the past in pursuit of its scientific goals; here, the committee advocates that this same coordinated effort be aimed at RVs.

A next-generation EPRV initiative building on the success of the NASA and NSF collaboration that yielded the NEID project is urgently needed. Research teams should work together on comprehensive databases that self-consistently combine the longitudinal coverage and high-cadence measurements from multiple instruments and telescopes forming a global network (Brown et al., 2013). One of the top priorities for such an initiative would be the development of a comprehensive and rigorous EPRV error budget that is empirically validated in the laboratory and at the telescope, and has predictive power for arbitrary spectrograph designs. The error budget should consider changes in RV stability over long periods of time and wavelength calibration standards. Mitigation schemes for stellar variability and differential telluric absorption are an immediate need and should be explored by theorists, statisticians, observers, heliophysicists, and instrument builders. Comprehensive studies across both the visible and near-infrared portions of the spectrum should be performed to compare wavelength calibration, stellar variability correction, injection of starlight into tiny fibers (including single mode), and compensation for differential telluric absorption. The EPRV initiative should culminate in the development and use of next-generation facilities that deliver cm/s radial velocity measurements. Ultimately, pushing RV precision and accuracy to several cm/s is a grand challenge in this field that requires a centrally coordinated approach to systematically address each source of noise.

> **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.**

Transit Timing Variations

Multiplanet systems are known to be common (Lissauer et al., 2012; Batalha, 2013); they also tend to form compact orbital configurations, making transit timing variations (TTVs) a powerful method for studying gravitational interactions and estimating exoplanet masses (Holman and Murray, 2005; Agol et al., 2005). In the TTV technique, the masses of planets can be deduced by observing the signature of planet-planet interactions leading to perturbed (i.e., non-Keplerian) orbits. The orbital perturbation is seen through changes in the time of transit of planets. In a number of cases, such as the TRAPPIST-1 system, the parent stars of terrestrial planetary systems are too faint or spin too rapidly to be studied with RVs (Gillon et al., 2017). TTV studies will continue to be relevant for TESS objects of interest, but the limited baseline (compared to Kepler) will result in degeneracies in planet mass and eccentricity (e.g., Lithwick et al., 2012). These can be ameliorated to some extent with observations of subsequent transits by other facilities, including CHEOPS, and in some cases RV can disambiguate and refine the results derived from TTV measurements, and vice versa.

Astrometry

Astrometry is less sensitive to stellar variability than the Doppler method (Shao et al., 2018, white paper). Given the reasonably large field-of-view (FOV) required to optimize the number of reference images used for calibration and pixel sampling, astrometry also offers a significant target multiplexing advantage compared to single-object techniques. Astrometry removes the orbital inclination ambiguity of radial velocity measurements and is also sensitive to planets with larger orbital separations (given a sufficiently long survey baseline), complementing the parameter space explored by Kepler and radial velocities.

The most precise astrometric observations conducted to date are of order 10 μas for bright ($G < 15$) stars from the GAIA mission (Lindegren et al., 2018). This level of precision is sufficient to detect gas giant planets amenable to direct imaging follow-up with GSMTs, including young planets. The precision of astrometric measurements conducted from the ground are an order of magnitude larger (Ghez et al., 2008; Sahlmann et al., 2014). Reaching the sensitivities needed to detect Earth-mass planets requires observations with precisions at roughly the $\sigma = 0.1$ μas level, which are generally believed to only be obtainable from space.

Astrometry has a spotty history involving exoplanet false-positive detections and the cancellation of the Space Interferometry Mission (SIM). Only two "high confidence" exoplanets have been discovered with this technique (Muterspaugh et al., 2010), neither of which has been independently confirmed. Despite its intrinsic merit, astrometry has not been viable as a search technique, given that a space mission is needed for large samples and low-mass planets. It has also been somewhat supplanted due to the anticipated detection of terrestrial planets using the EPRV method. Although not an immediate priority for the exoplanet community, astrometry is being considered for the proposed LUVOIR mission. Technology readiness levels (TRLs) and hardware maturation plans should ideally be studied in parallel with the above-mentioned ground-based EPRV efforts.

> **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.

THE NEED FOR DETAILED STELLAR CHARACTERIZATION

An understanding of exoplanets is inextricably linked to an understanding of the stars they orbit. Moreover, the ability to detect planets and the precision with which researchers can determine their properties is often limited by knowledge of the star.

Connecting the Exoplanet and Stellar Astrophysics Communities

As described in the section "Exoplanet Masses," earlier in this chapter, variations in the stellar photosphere are currently the dominant source of uncertainty for RV determinations of the planet mass, and as shown below, the same is often true for transit studies of the exoplanet atmospheres. As described earlier, in order to achieve the RV precision to detect an Earth-mass planet orbiting a Sun-like star, increased observational cadence, spectral resolution, SNRs, and stellar activity monitoring are required to disentangle stellar from planetary signals. This approach should include close collaboration with the solar and stellar astrophysics communities, including theorists, modelers, and observers (Wright and Sigurdsson, 2018, white paper).

Fortunately, it is not a one-way street: the high quality of the exoplanet-grade data has proven to be of great value to the stellar astrophysics community (e.g., Brogaard et al., 2018; Handberg et al., 2017; Campante et al., 2016). However, the use of such data by the stellar astrophysics community is impeded in part by the fact that RV data are not always public, or, even when public, can require highly specialized knowledge that is often unavailable to non-team members, yet critical for the proper analysis of the data. The RV community is also plagued with important and increasingly recognized data analysis challenges (e.g., Dumusque, 2016; Dumusque et al., 2017) that can influence the measurement of the stellar signal. Moreover, RV observations are usually taken at precisions that are of great interest to stellar astrophysicists, yet at cadences and over time spans that are more optimized for exoplanet detection. As discussed in the section "Exoplanet Masses," leveraging the stellar expertise that is already available, including at the instrument design level, increases the likelihood that the stellar variability barriers to the RV detection of Earth-mass planets are ameliorated. Examples of specific areas of possible collaboration between the RV and stellar astrophysics communities include (1) using three-dimensional (3D) solar photosphere models in order to assess which spectral lines are most diagnostic of solar-like variability; (2) observing the Sun as a star in RVs (e.g., Dumusque et al., 2015; Haywood et al., 2016); (3) combining 3D hydrodynamic simulations of stellar photospheres with high spectral resolution observations of specific absorption lines of stars with spectral types other than solar, in order to assess the variations to which those lines are most sensitive (e.g., Dravins et al., 2018); and (4) guidance from stellar modelers to optimize the spectral coverage at the instrument design stage in order to best monitor instrinsic stellar variations.

Stellar Variability and Surface Heterogeneity Across the Electromagnetic Spectrum

Heterogeneities on stellar photospheres are ubiquitous. At optical and infrared wavelengths, such regions of various temperatures, and thus differing local emission spectra, will corrupt the wavelength-dependent transit measurements of any planet (Figure 4.11).

Permission Pending

FIGURE 4.11 Schematic of the effects of differing stellar inhomogeneities along the transit chord compared the integrated stellar disk on exoplanet transmission spectrum. Such differences lead to apparent variations in the transit depth as a function of wavelength, which could incorrectly be attributed to sources of opacity in the planetary atmosphere. SOURCE: Rackham et al. (2018).

For example, dark spots on the stellar surface that intersect the transit chord result in a shallower transit, while spots that do not intersect the chord result in a deeper transit (e.g., Pont et al., 2013). The opposite is true for bright regions, such as faculae on the photosphere and plages on the chromosphere. As researchers push transmission spectroscopy to study the atmospheres of ever smaller planets, understanding and correcting for these effects become ever more important. At UV and X-ray wavelengths, the active regions have greater temperature contrasts to their surroundings and are more extended than active regions in the optical and IR; even for giant planets these inhomogeneities can measurably impact the transit signal (Llama and Shkolnik, 2015).

There are several areas of concern. First, researchers need to pay attention to the variability of the stellar active regions over the duration of the observations used to construct the transmission spectrum of the planet. This can be due to short-term (minutes to hours) changes in the photosphere caused by flares and long-term changes (days to months) due to stellar rotation. Very long term (over years) changes, such as stellar magnetic cycles (Duncan, 1991; Baliunas et al., 1995; Jeffers et al., 2018) may also add uncertainty when compiling transit (and precise RV data) acquired over months to years. This can be somewhat mitigated by collecting many transits in the same bandpass, in order to average over the effects of such stellar inhomogeneities.

Second, the stellar spectrum of the transit chord is not identical to the stellar spectrum of the integrated disk, which will add error to the measured size of the planet at a particular wavelength (Figure 4.11; Zellem et al., 2017; Rackham et al., 2018). In some applications, these effects will be negligible, but in others, such as planets transiting active stars and M dwarfs, they will preclude an accurate measurement of the atmosphere. Both variability and surface inhomogeneity become increasingly problematic at short wavelengths, such as in the far-UV (FUV), where chromospheric emission lines such at Lyman-alpha are being used to study the extended atmospheres of transiting exoplanets (e.g., Vidal-Madjar et al., 2003; Lecavelier Des Etangs et al., 2010; Kulow et al., 2014; Ehrenreich et al., 2015). These concerns also directly impact plans to search at infrared wavelengths for atmospheric biosignature gases in the atmospheres of HZ planets. Although in the infrared these effects are lessened, they are not entirely eliminated (e.g., Rackham et al., 2018).

Impact of High-Energy Stellar Radiation on Exoplanet Atmospheres

A better understanding of the high-energy emission from host stars will allow for better interpretation of atmospheric features in exoplanetary spectra, and will inform the target strategy for an imaging mission. The near-UV (NUV; 200-300 nm) and far-UV (FUV; 100-200 nm) flux modifies the photochemistry of the atmosphere, potentially photodissociating important diagnostic molecules such as water, methane, and carbon dioxide (Figure 4.12). The extreme UV (EUV; 10-90 nm) also photoionizes, heats, and inflates the planet's upper atmosphere. The combination of this, with pick-up by the high-energy protons from the stellar wind, controls the mass loss rate of the atmosphere (Koskinen et al., 2010; Tilley et al., 2017).

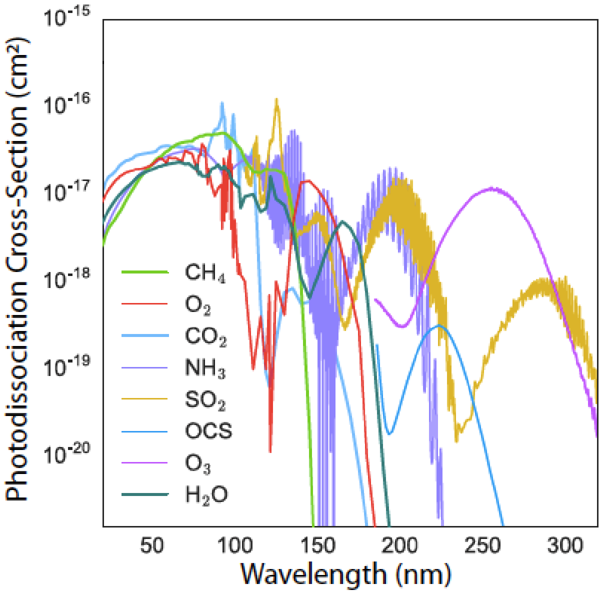

FIGURE 4.12 Photodissociation cross sections at ultraviolet wavelengths of many common planetary atmospheric trace gases, including biosignatures. SOURCE: E. Shkolnik, using data from high-resolution transmission (HITRAN) molecular absorption database (Gordon et al., 2017).

Lammer (2007) considered the impact of EUV emission on terrestrial planetary atmospheres and concluded that the atmosphere of an unmagnetized planet can be completely eroded in its first billion years. Magnetic fields of exoplanets may play a role in the protection of planetary atmospheres from erosion, but meaningful measurement limits are restricted to hot Jupiters (e.g., Zarka et al., 1997; Grießmeier et al., 2007; Shkolnik et al., 2008; Zarka et al., 2015; van Haarlem et al., 2013; and see reviews by Lazio et al., 2016; Shkolnik and Llama, 2017) and free-floating planetary mass objects (Kao, 2016).

Together, the FUV and EUV can produce hazes in reducing atmospheres (Zerkle et al., 2012) and ozone (O_3) in oxidizing atmospheres (Segura et al., 2003; Segura et al., 2005), both of which may strongly affect the observed planet spectrum (e.g., Bean et al., 2011; Kreidberg et al., 2014; Linsky et al., 2014; Shkolnik and Barman, 2014). Photochemical models of exoplanetary atmospheres require realistic inputs of high-energy stellar fluxes, slopes, variability and evolution.

For habitable zone terrestrial planets orbiting M dwarfs, the high-energy photon and proton flux is even more critical to understand, as the fluxes are at least five times stronger than the fluxes received at 1 AU from a solar-type star (France et al., 2016). The UV flux emitted during the super-luminous pre-main sequence phase of M stars drives water loss and photochemical O_2 buildup for terrestrial planets within the HZ (Luger and Barnes, 2015). This phase can persist for up to a billion years for the lowest mass M stars (Figure 4.13; e.g., Stelzer et al., 2013; Shkolnik and Barman, 2014; Schneider et al., 2018). The slope of the high-energy spectrum of M dwarfs is also very different than for the Sun, with FUV to NUV flux ratios being greater than 1000 times that of the Sun (Figure 4.14; France et al., 2012; Miles and Shkolnik, 2017). This is problematic, as it enables several photochemical pathways to creating false positive biosignatures in the form of abiotic production of O_2 and O_3. In some scenarios, false negatives of biosignatures are also a possibility through the photodissociation of the biosignature gases (Meadows et al., 2017).

Finding: Stellar UV emission impacts planetary habitability as well as the interpretation of putative atmospheric biosignature gases.

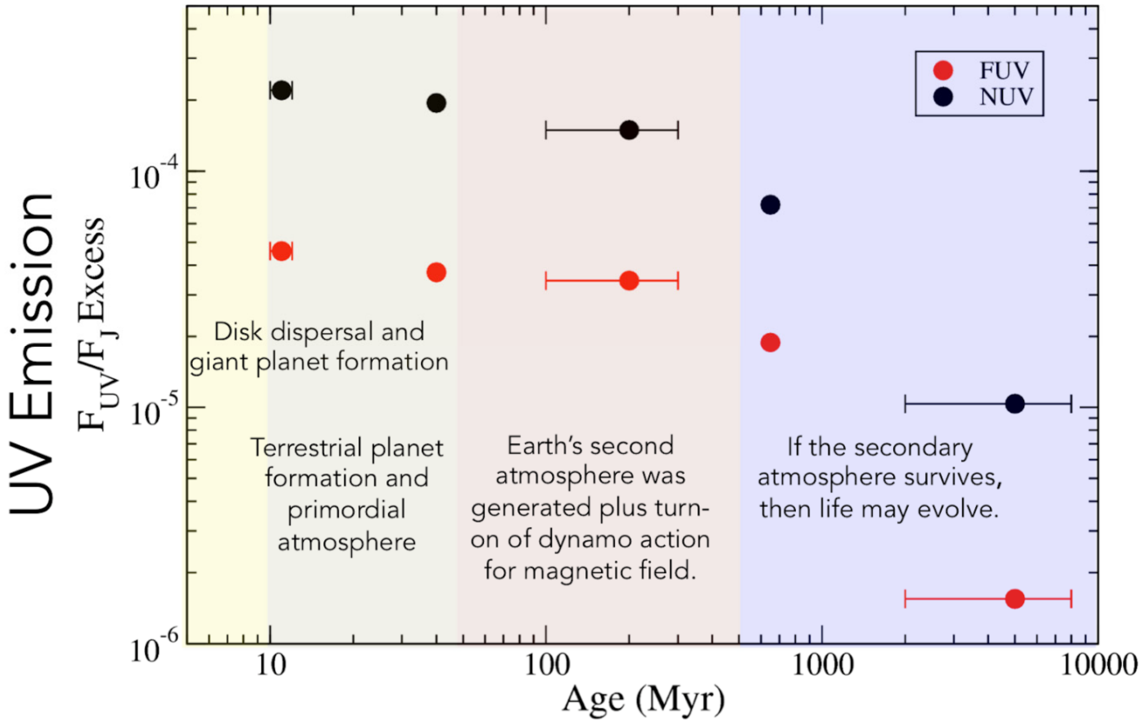

FIGURE 4.13 GALEX snapshot observations of a large sample of M stars display a drop in median values of FUV and NUV flux with increasing age, yet observed activity levels span 1 to 2 orders of magnitude. SOURCE: Shkolnik and Barman (2014).

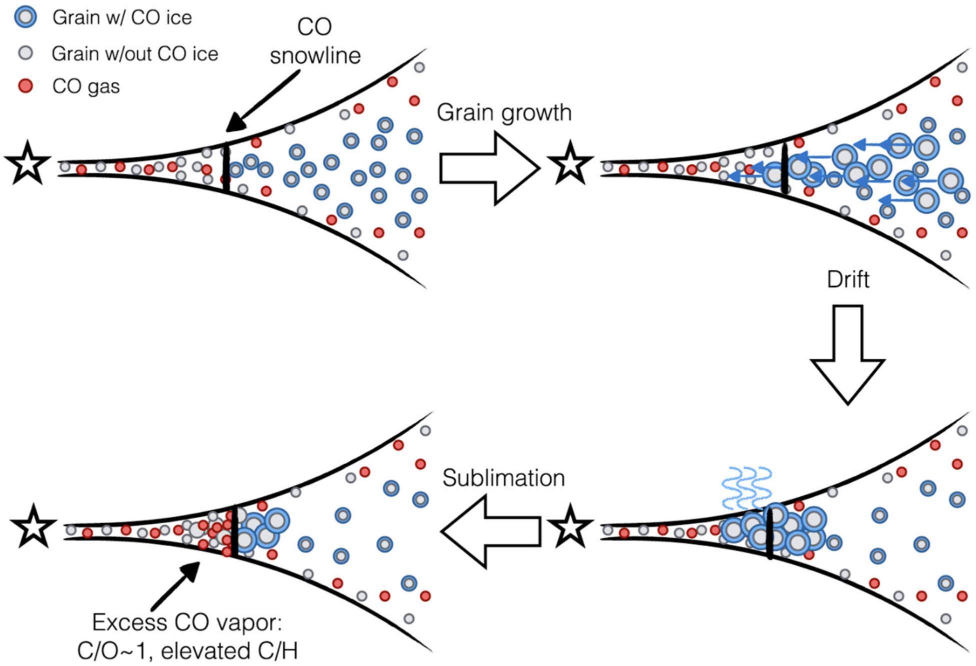

FIGURE 4.14 The drift of grains through a disk is dependent on their formation from dust and their migration due to interaction with the gas. As they migrate, they can change the chemistry of the remaining gas and the solids that form planetesimals and then planets. SOURCE: Oberg and Bergin (2016).

Measuring and Predicting Ultraviolet Emission from Stars

Photoevaporation models of protoplanetary disks (e.g., Clarke et al., 2001; Owen et al., 2010) and photochemical planet atmosphere models for all types of exoplanets, from Earths to Jupiters, need input stellar UV fluxes (Segura et al., 2010; Line et al., 2010; Kaltenegger et al., 2011; Hu, 2012; Kopparapu et al., 2012; Moses et al., 2013) across planet formation and evolution time scales. Photometric data from the Galaxy Evolution Explorer (GALEX) demonstrated that median UV flux appears to stay at the "saturation" level, an empirical maximum emission also observed in X-rays, for a few hundred million years for early M stars, and out to a Gyr for late-M stars (Figure 4.14). Furthermore, UV emission spans 1 to 2 orders of magnitude at every age, likely due to flaring events and intrinsic differences in activity from star to star. Existing HST UV spectra of old, relatively inactive, M-dwarf planet hosts reveal a variety of flaring activity within the 0.5-2 hour exposures (France et al., 2013; Loyd and France, 2014), with some emission lines flaring by as much as a factor of 10. Using round-the-clock visible-light monitoring, Davenport et al. (2014) analyzed 11 months of Kepler data of the active M4 star GJ 1243 and found over 6000 individual flaring events averaging 19 flares per day. Even for the slow-rotator and HZ planet host, Proxima Centauri, Davenport et al. (2016) report a strong optical light flare rate of about 2 per day, with weaker flares predicted to occur 63 times per day and super-flares occurring at the rate of approximately 5 per year (Howard et al., 2018; MacGregor et al., 2018). Note that the associated particle flux during these flares is completely unconstrained at this time, but will be important in understanding the combined effects of photons plus particles on planetary atmospheres (e.g., Tilley et al., 2017).

Current access to stellar FUV and NUV spectra is solely available with HST, whose sensitivity to these wavelengths is degrading over time. The Russian-led World Space Observatory, a 1.7-meter UV telescope, is aiming for a 2023 launch, but there is no such planned NASA mission, ultimately leaving the U.S. astrophysical community without access to the UV for many years. Small satellites can help fill this UV gap. NASA recently funded the development of two new small UV telescopes housed in CubeSats: the Colorado Ultraviolet Transit Experiment (CUTE), an NUV low-resolution spectrometer (Fleming et al., 2018), and the Star-Planet Activity Research CubeSat (SPARCS), an FUV and NUV photometer (Shkolnik et al., 2018). Both experiments are dedicated to the temporal characterization of high-energy emission from exoplanet host stars.

> **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 to understand their habitability.

EUV fluxes are not accessible due to the attenuation of the interstellar medium. For these, reliance on scaling laws from the FUV and X-ray is insufficient given the wide range of quiescent and flare emission levels. These facts necessitate a detailed grid of upper-atmosphere models, across stellar mass, age and flare state, in order to predict the EUV flux and variability. Atmosphere models (e.g., Phoenix; Hauschildt et al., 1997; Allard et al., 2001) substantially underpredict the UV emission from low-mass stars and do not model the upper atmosphere, which is brightest at high-energy wavelengths. Since access to the NUV and FUV is limited, and the EUV is inaccessible, there is a need for upper-atmosphere models that can accurately predict these fluxes. Existing models could be modified to include the non-local thermodynamic equilibrium (LTE) radiative transfer prescriptions needed for predicting the upper atmosphere emission; efforts to build such empirically guided models are just beginning (Peacock et al., 2015; Fontenla et al., 2016).

System Ages for Planetary Formation and Evolution

Planets evolve throughout their lifetimes, and hence knowledge of their ages is an important input to interpreting their properties. The ages of stars are estimated from several techniques, each of which has observational and intrinsic astrophysical regimes in which it works best. Stellar age determination methods include asteroseismology, cluster or young moving group membership, lithium absorption, surface gravity, isochrone fitting, and rotation-activity relations (Soderblom, 2010).

For stars younger than 300 Myr, ages can be measured with relatively high precision. This is valuable in particular to the discovery and characterization of self-luminous giant exoplanets with direct imaging, for which the age of the system determines the inferred mass of the companion through planetary model atmospheres (e.g., Bowler, 2016). Finding planets around young stars using the RV and transit methods is intrinsically difficult due to their high levels of magnetic activity and rapid rotation, although transit surveys have recently succeeded in some young open clusters (David et al., 2016, 2018; Livingston et al., 2018; Mann et al., 2016, 2017; Pepper et al., 2017). However, the vast majority of planets orbit inactive, slowly rotating, and therefore older (>1 Gyr), main sequence stars, and this regime is where many empirical age-dating methods break down (Sodorblom, 2010). Asteroseismology can provide precise age measurements for older main sequence stars (e.g., Brown et al., 1994; Chaplin et al., 2014; Campante et al., 2015), but only if they are sufficiently bright, and it requires long baselines, rapid (less than approximately 1 minute) cadence, and high-precision photometry. These considerations, and the drop in amplitude with decreasing stellar mass, makes asteroseismology generally unusable for main sequence stars much less massive than the Sun given currently achievable photometric precision. Gyrochronology, the evolution of stellar rotation with age, is another opportunity to measure ages for solar-mass stars for ages less than about 5 Gyr (e.g., Barnes et al., 2016), but has its own empirical inconsistencies, as well (e.g., Angus et al., 2015).

> **Finding:** Understanding of exoplanets is limited by measurements of the properties of the parent stars, including stellar mass, radius, distance, binarity, rotation period, age, composition, emergent spectrum, and variability.

PLANET FORMATION

Planet formation studies require multiple techniques across multiple wavelengths to trace both the gas and dust over the scales relevant to planetary architectures. Because planets exist at semimajor axes from several hundredths of an AU to several hundreds of AU, and because planets may form from material that migrates over the full sizes of disks, the relevant disk temperatures span 1800 K (the first temperature at which solids condense) to 20 K (where ices in outer disks play critical roles in the formation chemistry). The disparate temperatures immediately imply the need for observational wavelengths spanning from the optical to the radio. From the Solar System, one spatial scale emerges as particularly important—namely, the division at 4 AU between primarily rocky material and the regime where ice and gas dominate. This physical scale needs to be observed around young stars. The nearest large groups of stars younger than 10 Myr sit at 140 pc, so the spatial resolution needs to be at least 10 mas.

A central goal of planet formation studies is to be able to predict the properties of the exoplanet population, including mass, density, multiplicity, and semimajor axes, from the range of initial conditions of the disks. Because solids migrate through disks, the history of planet formation impacts the final population synthesis. This section provides an overview of the important paths toward understanding planet formation.

> **Finding:** An understanding of planet formation requires a census of protoplanetary disks, young planets, and mature planetary systems across a wide range of planet-star separations.

Key inputs are the initial disk mass, disk size, and disk lifetime. Only the last of these is well constrained currently, based on studies of disk accretion and disk continuum emission from young stars in clusters and associations of varying age.

The bulk of the disk mass is in molecular hydrogen, which is difficult to measure because it lacks strong rovibrational transitions as a consequence of having no dipole moment. Tracer gases such as CO show strong depletions from the gas phase (e.g., Kama et al., 2016; McClure et al., 2016; Schwarz et al., 2018), either due to photodissociation or condensation and incorporation into icy material. Dust disk masses are uncertain due to uncertainty in dust opacities, varying opacities from different-size grains, and high optical depths. Furthermore, because small solids drift with respect to the gas in disks, solid-to-gas ratios likely vary with distance from the star. This process may significantly deplete solids in the outer regions of mature disks, where dust is most likely to be optically thin and dust disk masses are most easily measured. Direct measurements of the bulk gas over time are the only way to measure the properties that set the time scale for planet formation and dictate the formation and migration physics of large bodies. ESA's Herschel Space Telescope measured masses for only three disks (Bergin et al., 2013; McClure et al., 2016). A future cold (4 K) telescope that is 5× larger than Herschel could detect many hundreds of disks at least as massive as the minimum mass solar nebula (Pontoppidan et al., 2018, white paper).

> **Finding:** Understanding the time scale and mechanism, including turbulence generation, for the dispersal of disk gas is key to understanding the final chemistry of planets and architectures of systems. Measurement of HD is the only direct method for directly measuring disk masses. The fundamental rotational transition of HD is at 112 microns, and therefore its detection requires a large, cold-space telescope.

Disk sizes can be observed in dust, gas tracers, and hydrogen deuteride (HD), and both by spatially resolving the disk and by looking at velocity-resolved spectral lines. Atacama Large Millimeter/Submillimeter Array (ALMA) can pursue submillimeter emissions to trace large grains and kinematically resolved gas. HST, JWST, and large ground-based telescopes (e.g., SPHERE on the VLT, GPI on Gemini, and instruments to come on the GSMTs) have made and will make images in scattered light that show the extent of small dust grains, which are coupled strongly to gas and which trace the outermost reaches of disks.

Disk lifetimes can be refined by studying the gas-to-dust ratio as a function of radial location in the disk. This will require a combination of techniques that can trace both gas kinematics and location, as well as dust size and location. Large ground-based optical and infrared telescopes and GSMT can play a leading role in this with spatially resolved, high-resolution imaging and spectroscopy that can trace both gas kinematics with spectral resolution and gas location with spatial resolution. ALMA and even higher spatial resolution interferometers can also play a big role in both gas kinematics and dust continuum levels in disk midplanes.

Measurements of disk chemistry, particularly in the midplane of disks, are required to understand the diversity of compositions that exoplanets may have (Figure 4.14). JWST will make great strides on the warm molecular layer and gas composition in optically thin inner holes, particularly for water and organic molecules, following on successes from Spitzer (e.g., Carr and Najita, 2008) and large ground-based telescopes (e.g., Salyk et al., 2008; Mandell et al., 2012). ALMA is making outstanding progress on snowline locations and chemistry more generally in the cool, outer disk (e.g., Qi et al., 2013; Walsh et al., 2016). Midplane chemistry in the 1-5 AU region is challenging because of very high optical depths. However, it is there that planetesimals will form, so the midplane (and the circulation between the midplane and upper layers of the disk that brings in new chemical constituents) will dictate planetary compositions. Ultimately, it would be fruitful to connect studies of Solar System comets, asteroids, and meteorites including timing of differentiation, isotopic trends, and relationships between high- and low-temperature condensates with conditions measured in protoplanetary disks (Figure 4.15).

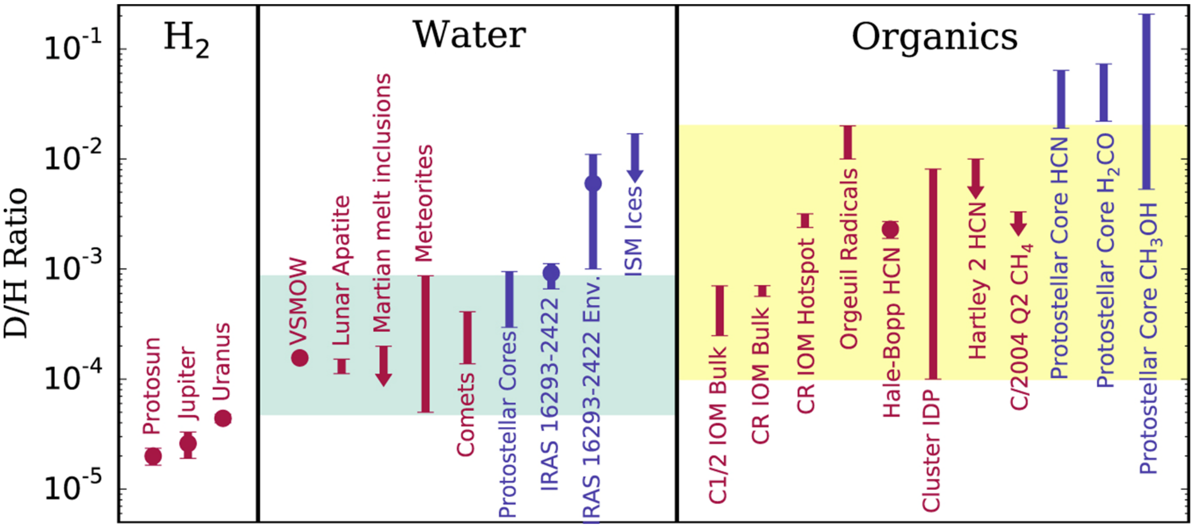

FIGURE 4.15 Comparison of the D/H ratio for objects inside (red) and outside (blue) the Solar System. There is a large range of D/H in the Solar System, as shown by the teal and yellow bands. D/H enrichment happens at low temperatures, and the very large enrichments seen in some Solar System materials must be inherited from the interstellar medium. Models show that Earth's water comes, at least in part, from the interstellar medium via the planetesimals that formed Earth (Cleeves et al., 2014). Tracing the chemical pathways in disks and measuring the spatially resolved disk chemistry in other systems is crucial for understanding the capability of other planets to host life. SOURCE: Cleeves et al. (2016).

In the future, an enhanced interferometer could be essential for this problem, as mm to cm wavelengths would provide for new molecular tracers and higher spatial resolution; a cold space telescope would permit us to trace warm water vapor and its incorporation into solids. Astrochemical theory and laboratory measurements will be essential for correctly interpreting observations including improved understanding of chemical networks at various temperature and pressure regimes, grain opacities, porosity, size distributions, and the processes of growth and sticking.

> **Finding:** Disk chemistry in the midplane affects the compositions of the resulting planets. A cold space telescope, high-resolution spatially resolved infrared spectroscopy, and ground-based mm interferometry would enable significant advances and permit meaningful comparisons to studies of comets, asteroids, and meteorites from the Solar System.

Observations of young planets in disks will provide the ground truth for the otherwise indirectly inferred time scales of planet formation and permit studies of the dynamical interactions between disks and planets. From RV and direct imaging studies, there are indications of massive planets around very young stars (less than 5 Myr old; Kraus and Ireland, 2012; Sallum et al., 2015; Donati et al., 2016; Johns-Krull et al., 2016; Keppler et al., 2018). These systems will be ideal places to test the physics that ties planets to their disks, but more need to be found. Direct imaging at key wavelengths is essential and will be greatly enabled by the GSMTs. In particular, H-alpha emission would verify the presence of a massive, compact body (e.g., Wagner et al., 2018), and infrared emission would determine its luminosity and, by inference, its mass (e.g., Morzinski et al., 2015).

ALMA has resolved ring-like structures in a number of protoplanetary disks (Figure 4.16). Further progress on the imaging of disk structure at a variety of wavelengths will be essential to figure out how these structures formed. JWST, ALMA, and GSMTs are all complementary because they have different sensitivities to grain size. The size distribution and composition of grains inside and outside of the gaps will show if pressure bumps or condensation fronts are the more likely causes of gaps, or whether planetary-size objects form them. Observations at higher spatial and spectral resolution of gas, combined with theory, may uncover if rings and gaps are caused by planets and, if so, what planetary properties can be inferred. Conversely, if the physics of planet-disk interaction is well understood, the size of gaps can be used to infer the presence of planets not massive or bright enough to be directly detected. An exciting forefront is looking at planet-gas interactions in disks. ALMA observations have uncovered the first of these (Pinte et al., 2018; Teague et al., 2018). High-resolution spectroscopy (R > 60,000) in the infrared is necessary to pursue the same type of interactions in warmer gas and with specific molecules.

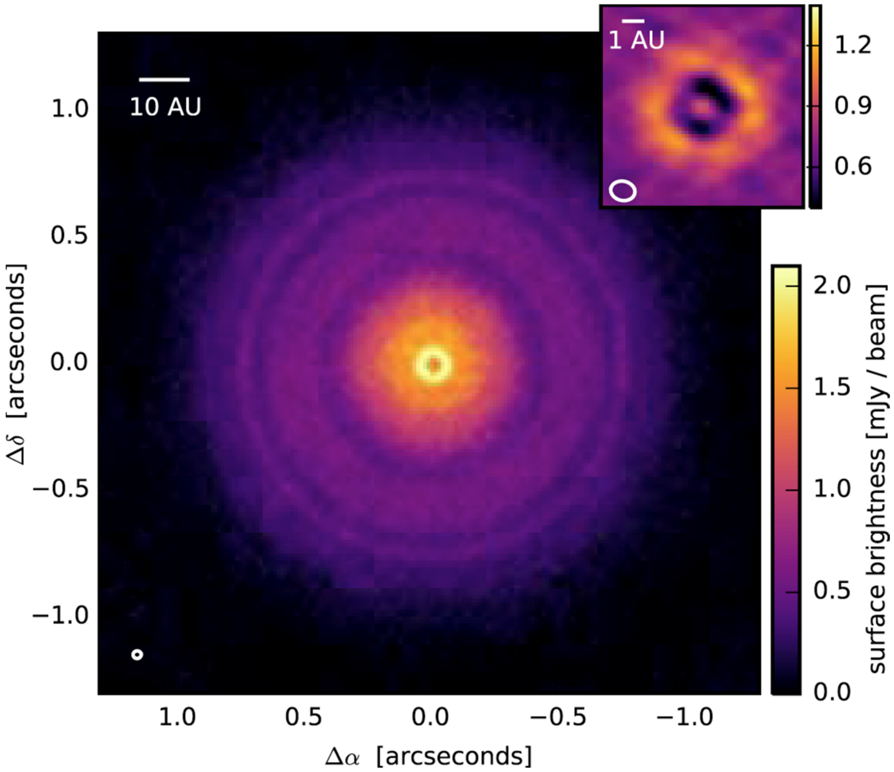

FIGURE 4.16 ALMA observations of the continuum emission from the nearest gas-rich protoplanetary disk, around TW Hya. These data reveal a series of concentric ring-shaped substructures. SOURCE: Andrews et al. (2016).

For slightly older systems, researchers should better characterize exo-zodiacal and cold debris disks. Detailed images of belt locations (only now becoming available with ALMA) will allow modeling of the system architectures. Measurement of dust compositions will allow constraints on the compositions of planets. JWST will make progress on this, but a large cold space telescope would allow the detection of Kuiper-belt levels of dust around nearby stars without confusion from background sources.

The ability to detect asteroidal-like belts may be particularly interesting for assessing the existence and habitability of any rocky planets. Ground-based interferometers (Very Large Telescope Interferometer [VLTI] and Large Binocular Telescope Interferometer [LBTI]) have detected hot inner dust but have not had the spatial resolution or sensitivity to look for clumps in the distribution that would be expected from planetesimals in resonance with planets. Detection of dust clumps that orbit stars would uncover planets otherwise hard to detect.

> **Finding:** The detection of young planets in disks will provide the ground truth for the time scale of planet formation and permit studies of the dynamical interaction between disks and planets. With the high spatial resolution of the GMT and TMT, researchers will be able to search the inner parts of planet-forming systems.

At the end of its prime mission in 2018, LBTI will provide limits will just reach a level that helps inform the size of a direct imaging mission (see the section "The Case for Imaging," earlier in this chapter). Furthermore, LBTI measures the thermal emission of the dust, whereas it is the amount of light that dust scatters that determines the background for direct imaging measurements. The conversion from thermal emission to scattered light surface brightness depends on the composition and size of the dust grains, which have yet to be measured. The WFIRST coronagraph could make progress on measuring scattered light exozodiacal levels and constrain dust clumpiness. LBTI could be extended to push down to Solar System levels of dust and explore the relationship between cold and warm dust. More theoretical and observational work on systems with detected dust could enable a better understanding of how and where remnant planetesimals produce dust.

The process of disk dispersal sets the time limit for planet formation and changes the composition of the disk including the gas-to-dust ratio that affects migration and planetary composition. Therefore, understanding the time scale and mechanism of disk dispersal is key to understanding the final chemistry of planets and architectures of systems. Four types of observations constrain the angular momentum loss of disks: (1) signatures (such as H-alpha emission) of accretion onto the central star; (2) wind tracers such as Doppler-shifted and broadened forbidden lines of atomic species that show outflowing gas; (3) broadened molecular lines arising in disks where the broadening is from turbulent motion of the gas; and (4) X-ray/UV measurements of young stars over time. The first of these is a well-developed technique, although more synoptic observations are needed to elucidate how much mass is accreted in a steady state versus outbursts, and how those accretion bursts affect the other properties of the disk. Direct measurements of disk photoevaporation or winds would benefit from spatial resolutions afforded by ground-based telescopes with adaptive optics than can work at red visible wavelengths. More measurements of turbulence are needed to understand the turbulence distribution, in disks at different evolutionary stages, at closer distances to the stars, and at different scale heights. Only then can researchers test whether magneto-rotational instability models can drive accretion and whether turbulent concentration of dust works to form planetesimals rapidly. More capable spatially resolved, high-resolution spectroscopy from the infrared to millimeter wavelengths will be essential.

The X-ray luminosities of young stars over time may control their disk dissipation rates and help set the disk chemistry through their penetrating ionization of disk gas. New facilities with higher sensitivity would be able to measure X-ray luminosities and spectra for very low mass stars (below 0.5 M_{sun}) that were too faint for Chandra (e.g., Prisinzano et al., 2008; Kastner et al., 2016).

> **Finding:** An understanding of planet formation would permit the inference of some planetary properties that cannot be directly probed. A better understanding of the link between stellar composition, disk composition, planetary composition, and atmospheric composition is necessary to translate observations of planetary atmospheres into statements about bulk planetary compositions.

THEORY OF EXOPLANET EVOLUTION, INTERIORS, SURFACES, AND ATMOSPHERES

Theory and observation in the exoplanet field are inexorably coupled. While for some areas of exoplanets theoretical modeling has moved well ahead of the current data, there are a number of areas in which the available data, although limited, are already charging ahead of theoretical investigations. Some outstanding challenges in the theory and modeling of exoplanets that need to be addressed in order to achieve the two goals described in Chapter 3 are discussed below. As outlined here, achieving these goals requires collaboration between research groups with different and overlapping expertise.

Specific Scientific Challenges in the Theory of Exoplanets

Planetary Evolution

The long-standing question of whether giant planets can form through disk instability as well as core accretion has given way to a more nuanced question of the accretion histories of these objects. Planets that form through large-scale quasi-adiabatic processes will form with high entropy and therefore high initial luminosity; those that accrete most of their mass through a compact shock, as scientists think Jupiter perhaps did, will have a low initial luminosity. This record of a planet's entropy of formation and subsequent cooling history is thus fossilized in its present day luminosity for planets less than about 100 million years of age. Extracting meaningful constraints relies on comparing the observed mass and emitted flux to models of the planet formation process. A second question relates to the inflated radii of many hot Jupiters. The range of theories broadly bifurcate into those that provide an additional energy source over the lifetime of the planet, and those that trap in heat from formation and slow the planetary cooling process. Recent advances include applying statistical techniques to the full population of known hot Jupiters (Thorngren and Fortney, 2018), which conclude that Ohmic heating (Batygin and Stevenson, 2010) is the likely mechanism for transferring heat from the atmosphere into the interior. Modeling the magnetic environment of a close-in exoplanet is challenging and poorly constrained by observations. Magneto-hydrodynamic models detailing the interactions between magnetic fields and the planet's atmosphere and interior are currently underdeveloped.

For small rocky planets, the big questions that need to be addressed by theoretical modeling include the histories of volatile delivery, and atmospheric outgassing and escape, which are mitigated by both the host star irradiation and the dynamical history, including collisions. As described previously in the section "Stellar Composition, Planet Formation, and the Delivery of Volatiles" in Chapter 3, evidence suggests that some volatile-rich Earth-size planets may be have formed in outer orbits and then migrated inward. Future key work will focus on models for terrestrial planet formation and migration around different types of stars, which can illuminate the initial composition of the terrestrial planet, and interactions between other components of the system that can affect volatile delivery.

XUV and particle fluxes from the host star can strip a terrestrial planetary atmosphere completely (Garcia-Sage et al., 2017; Dong et al., 2018) or modify the composition of the atmosphere via escape (Schaefer et al., 2016, 2018) and photochemistry (Segura et al., 2005; Rugheimer et al., 2015). Ocean loss can also be driven by the star, which will also modify the atmosphere (Luger and Barnes, 2015). These compositional modifications will, in turn, affect the planetary climate and stellar UV flux incident on the planetary surface (Meadows et al., 2018). Tidal deformation produced by gravitational interaction between a star and planet on an elliptical orbit could also possibly heat the planetary interior, drive off a planetary ocean, enhance tectonic activity, and shut down the magnetic dynamo (Driscoll and Barnes, 2015; Meadows and Barnes, 2018). It is likewise essential to couple such studies to the processes of atmospheric outgassing. It will be important to use atmospheric, interior, and orbital evolution models, as well as climate, photochemistry, radiative transfer, and interior and tidal heating models to understand the history of the production of secondary atmospheres and the sculpting of these atmospheres by environmental factors.

The anomalously low occurrence rates for highly irradiated planets around 1.5 R_E from Kepler data appears to indicate that small gas-rich planets fail to survive on close-in orbits (Fulton et al., 2017, 2018), and provides urgent motivation for renewed theoretical work on this problem.

Planetary Interiors

Models of interior structure are the primary mechanism through which researchers convert mass and radius data to an understanding of the bulk composition of the planets. Degeneracies are a well-known problem in interior structure modeling. As a result key properties such as the core mass fraction or the total thickness of a hydrogen-rich gas layer cannot be uniquely constrained. This is a fundamental issue that cannot be overcome with improved interior structure models, but clever and innovative workarounds may exist. For example, detailed measurements of the composition of an exoplanet atmosphere may indicate the makeup of deeper regions of the planet's interior, or the presence of a magnetic field may be tied to the structure of the planet's core. For these reasons innovation in interior structure modeling and its relation to other exoplanet observables is of significant value to make headway.

The equations of state (EOS) of high-pressure planet-forming materials (ices, rock, and even H/He gas) are not always well known over the relevant range of parameter space. Remedying this shortcoming requires additional laboratory experiments and ab initio calculations (see below). Furthermore, mixing of materials between layers is typically treated simplistically in exoplanet models (full mixing of H_2O and H/He layers, e.g., Nettelmann et al., 2010, and Valencia et al., 2013; or no mixing at all, e.g., Rogers and Seager, 2010). Such differences in treatment can result in significant differences in inferred planetary composition. Improved self-consistent treatments of mixing could remove a key source of uncertainty in interpreting exoplanetary mass-radius measurements.

Planetary Surfaces

In the quest for discovering habitable exoplanets, remote sensing of planetary surfaces is highly desirable, both to establish the presence of liquid water and the local conditions under which a potential biosphere is operating. However, aerosols or thick atmospheres will challenge researchers' ability to detect planetary surfaces. Furthermore, degeneracies in exoplanet spectra may make it impossible to credibly confirm the presence of a planetary surface. Related outstanding theoretical work includes the following:

- Which planets should have a well-defined surface?
- How do researchers model surface fluxes of constituent gases, both sources and sinks? These can include volcanism, biology, and the carbonate-silicate cycle.
- How do researchers establish the relative covering fractions of oceans and continents, and their distributions over the planetary surface using mapping techniques, inversions, or retrievals? In the case of continents, what are their surface materials and elevation profiles? How do these, in turn, affect atmospheric circulation?
- How prevalent are planets with exotic surfaces, such as lava worlds or desert worlds?

Atmosphere Modeling

Significant effort has been put into the modeling of exoplanet atmospheres, but substantial gaps and multiple disparate computational approaches remain. To plan and interpret the data that researchers envision obtaining (see the sections "The Case for Imaging" and "Opportunities to Characterize Planets Through Transits," earlier in this chapter), the shortcomings of current modeling efforts need to be addressed.

Aerosols

Aerosols are a commonplace in transmission spectra (Sing et al., 2016; Crossfield and Kreidberg, 2017), yet accurate modeling of aerosols is a challenge, even for Solar System planets. The difficulties lie in the broad range of chemical and physical processes that need to be well understood for a successful aerosol model. These include the aerosol formation process (the direct condensation of gases, or photochemically induced formation of large molecules), the coagulation and particle nucleation processes, and the atmospheric transport of aerosol particles. Furthermore, the composition of the aerosols will be difficult to ascertain. These challenges are compounded by the fact that most known exoplanets are much hotter than Solar System objects and are therefore expected to have exotic aerosols. Understanding aerosols has been a primary bottleneck in interpreting exoplanet spectra. Concerted modeling efforts are needed that attack the aerosol problem from many different angles, with a focus on the overlap and feedback between the different approaches.

Gas-Phase Chemistry

There are various treatments of exoplanet atmospheric chemistry. Thermochemical equilibrium approaches are computationally cheap and may be appropriate for hot atmospheres, in which reaction rates are fast. Chemical kinetics codes, which perform time-dependent calculations of reaction rates, photolysis reactions, and vertical mixing and evolve the atmosphere to a steady state, are computationally intensive, and are typically only applied in one-dimensional (1D) models. Chemical relaxation schemes that attempt to account for some aspects of the chemical kinetics approach have been applied sparingly in 3D general circulation models (GCMs; e.g., Cooper and Showman, 2006; Tsai et al., 2017). None of these computational approaches are able to include all possible chemical species or reactions, so in all cases choices are made for which atmospheric constituents require direct tracking. In some situations, important physics and chemistry can be left out. For example, it was recently realized that thermal dissociation of water and ionization processes lead to substantial H^- abundances in the atmospheres of ultra-hot Jupiters. The previously unmodeled effect of H^- opacity on the radiative transport and resulting thermal emission spectra for these planets is substantial (Arcangeli et al., 2018; Kreidberg et al., 2018; Parmentier et al., 2018; Mansfield et al., 2018). The validity and relative merits of differing approaches need to be explored across the full parameter space.

Modeling Approaches

Exoplanet modeling efforts bifurcate into one-dimensional (1D) versus three-dimensional (3D) models, and forward versus retrieval models. Each approach has its own merits and shortcomings. Briefly, 1D models can typically treat radiative and chemical processes in more detail but cannot treat any spatial inhomogeneities that exist in the atmosphere. Forward models include detailed physics and chemistry at differing levels of self-consistency, whereas retrieval codes recover the properties that are present in an atmosphere without necessarily linking those to a physical explanation. It will be beneficial to perform comparisons between different classes of models to determine the situations in which the various simplifications taken by each approach remain appropriate and where the agreement between disparate models breaks down.

Spectral Retrievals

While spectral retrievals are one of the specific types of modeling approaches, they deserve their own discussion because of their recent rise in popularity within the exoplanet community. Statistical techniques are applied to determine best-fit parameters and confidence intervals based on the level of agreement between observed spectra and large suites of forward models run in a Monte Carlo framework. A variety of approaches have been applied, including those that assume thermochemical equilibrium and those that assume well-mixed atmospheres but allow the abundances of individual molecules to vary independently. A range of prescriptions for the thermal structure have also been adopted. In general, it has not been possible for exoplanet retrievals to be fully coupled between the atmospheric chemistry, thermal structures, and cloud properties. This can result in physically implausible best-fit scenarios. Therefore, careful attention needs to be paid toward the range of allowed solutions and whether they are physically motivated. Furthermore, exoplanet retrievals are typically 1D and do not account for 3D atmospheric dynamics or variability. Retrieval codes rarely use line-by-line calculations because these are computationally intensive when running many models. In the era of JWST and beyond, as the quality of exoplanet spectroscopy improves, retrieval techniques will be called upon to include additional layers of complexity and self-consistency, motivating substantial commitment to further development in this area.

Overarching Challenges

The Need for Coupled Models

As described above, there are a great number of modeling approaches being applied to the characterization of specific aspects of exoplanets, including their physical structure, and the chemistry and physical conditions of their atmospheres. In principle, all of the aforementioned modeling approaches from the section "Specific Scientific Challenges in the Theory of Exoplanets" should be coupled, since there are important feedbacks between them. For example, the atmosphere forms the upper boundary of the planet's interior, and the interior forms the lower boundary for the atmosphere. It is important to track sources and sinks at the boundaries (both energetic and chemical ones), but this is rarely done self-consistently. In the atmosphere, dynamics can alter thermal structures and carry a system away from chemical equilibrium. Similarly, the 1D chemical kinetics codes that track photolysis reactions and vertical mixing can produce abundance patterns that differ substantially from chemical equilibrium, and those changes in composition have feedback on the radiative processes in an atmosphere. The formation of aerosols (clouds and haze) are also dependent on the local chemistry and stellar irradiation, and the formation of clouds in turn alters the energy transport.

While an ambitious end goal may be to produce an exoplanet model that fully couples together all of the chemical, mechanical, and energetic processes that shape a planet and its atmosphere, this is not technically feasible in the foreseeable future. Indeed, this is one of the reasons for the popularity of spectral retrieval codes in exoplanet characterization. Retrieval approaches acknowledge the unknown and uncertain aspects of forward modeling and provide another avenue for determining atmospheric and system properties. Instead, an approach of successively coupled models is needed, with a focus on determining which regimes of coupling are the most pressing for interpretation of observational data.

Model Validation

Exoplanet models are often applied to portions of parameter space where precious little data are available and that extend far from the well-studied regime of Solar System planets. For this reason, model validation is necessary. In some cases, this might mean verification of model outputs, as compared directly against experimental or observational data (e.g., validations with observations of Solar System planets). Other situations in which a well-calibrated benchmark data set is not available may necessitate individual research groups performing cross-comparisons of their models directly with one another.

Lab Measurements and Ab Initio Calculations

Theoretical calculations are only as good as the physics and chemistry provided as inputs. A current barrier in modeling the interiors and atmospheres of exoplanets is the lack of availability of laboratory and ab initio data. In many cases, the available data are extrapolated to situations far from their originally intended use. A white paper detailing the specific laboratory data needed by the exoplanet atmosphere modeling community (Fortney et al., 2016) described the following needs:

1. Molecular opacity line lists with parameters for a diversity of broadening gases, which are needed for radiative transfer calculations of atmospheres with diverse compositions;
2. Extended databases for collision-induced absorption and dimer opacities, which are also needed to model atmospheres of diverse composition;
3. High spectral resolution opacity data for relevant molecular species, which are needed as cross-correlation templates for interpreting ground-based high-dispersion spectra;
4. Laboratory studies of haze and condensate formation and optical properties, which are needed to predict and interpret the properties of aerosols in exoplanet atmospheres;
5. Significantly expanded databases of chemical reaction rates, which are needed to predict the compositions of exoplanet atmospheres that stray from chemical equilibrium; and
6. Measurements of gas photo-absorption cross sections at high temperatures, which are also needed to predict the nonequilibrium composition of irradiated atmospheres.

Additional laboratory and ab initio calculations are also required by researchers modeling exoplanet interiors, including improved equations of state (EOS) data. The set of expertise needed to respond to all of these needs is diverse and spans multiple research communities.

> **Finding:** The limited lab and ab initio data covering the parameter space relevant to exoplanets is a barrier to accurate models of exoplanet atmospheres and interiors. Mechanisms to increase collaboration between exoplanet astronomers and experimental physicists and chemists would help overcome this barrier.

More Flexible and Modern Codes

Many exoplanet modeling tools have heritage from codes developed decades ago in now-outdated coding languages, with hard-wired parameters, and under significant computer memory limitations. Because of this, many of these codes are not easily adapted to new planetary parameters, are proprietary to specific research groups, are hard to read, and often do not take advantage of modern coding techniques. Yet these same codes are often well cited and produce consistent research results. There is a need to modernize old codes and to produce new, fast, flexible, well-documented, and publicly available exoplanet modeling tools. Such software packages lower the threshold of entry for new members of the field and observers with less modeling background, and these tools can be adapted readily as new research results become available.

Improved Computing Resources

The following areas would benefit from the further development of national-scale high-performance computing resources:

- Dynamical simulations of planet formation and evolution with many bodies;
- Hydrodynamic simulations of protoplanetary disk formation and evolution, including simulations tied directly to the star formation process and nonideal magnetohydrodynamic simulations required to study disk accretion;
- Hydrodynamic simulations of planet formation, requiring resolution of a large range of physical scales;

- Hydrodynamic simulations exploring planet-disk interactions;
- Hybrid simulations of planet formation capable of simultaneously exploring more physical processes;
- Multidimensional spectral retrievals;
- Coupled models of atmospheric escape and photoionization; and
- Large-scale grids of GCMs.

Finding: Theoretical models are essential to plan and interpret observations of exoplanets, and are enabled by robust support via individual investigator grants.

Throughout Chapter 4, the committee has reached a number of findings that demonstrate that NASA has not fully realized the scientific yield of its exoplanets missions because the required theoretical, laboratory, and ground-based work to interpret exoplanet data has not been undertaken.

Recommendation: NASA should support a robust individual investigator program that includes grants for theoretical, laboratory, and ground-based telescopic investigations; otherwise, the full scientific yield of exoplanet missions will not be realized.

ASTROBIOLOGY

Observations and Studies to Support the Search for Habitable Environments and Life

The search for life begins with the search for habitable environments. Required observations include not just those that determine if a given planet is in fact habitable, but observations of nonhabitable planets that can serve as a baseline for comparison, as well as suites of observations of habitable zone (HZ) planets that can be used to study the diversity of outcomes of terrestrial planet evolution, including the habitable zone concept itself, as a function of planetary parameters and host star type.

Observations for Habitability Assessment and Biosignature Searches

The habitability assessment of potentially habitable planets will include a sequence of observations to determine the following:

1. The planetary mass, which in most cases will be done with radial velocities (see the section “Exoplanet Masses,” earlier in this chapter). If the planet is transiting as well, photometric and RV observations can be combined to determine the size and bulk density of the planet. Combined with a knowledge of the stellar elemental abundances, this will constrain the interior composition.
2. Whether or not the planet has an atmosphere. For example, in the case of a planet transiting a nearby M dwarf, this could be accomplished with JWST transit observations (e.g., Morley et al., 2018; Lustig-Yaeger et al., 2017).
3. The nature of that atmosphere (bulk composition and greenhouse gas census), and surface (for direct imaging), including possible surface pressure and temperature. These will be challenging to obtain, but could be pursued with transmission spectroscopy, thermal phase curves, secondary eclipses, infrared photometry or direct imaging spectroscopy (Meadows et al., 2018). These measurements could be compromised by the presence of cloud cover.
4. Orbit and rotational period. For directly imaged planets that may not have had their mass and orbit determined via RV or transit in step 1, then the orbit can be obtained from multiple

direct images of the planet, or from RV or astrometric measurements of the host star. The rotational period, which can indicate if the planet is synchronously rotating and governs climate regime and the likelihood of atmospheric collapse (Turbet et al., 2016, 2018), may be derivable if multiwavelength, time-resolved direct imaging observations can be used to map an inhomogeneous planetary surface (Pallé et al., 2008; Cowan et al., 2009; Fujii et al., 2017).

5. Whether glint or polarization signals from an ocean are observed. These signals should be sought at multiple points on the orbit to capture the phase-dependence of the glint signal (Robinson et al., 2010, 2014), and may be easier to detect if the planet is simultaneously mapped to identify the spatial extent of the ocean (Tovar et al., 2017).
6. Once planetary mass, size, rotation rate, the presence of an atmosphere, and a census of greenhouse gases are known, whether coupled climate-photochemical models can be used to constrain surface condition solutions.
7. Whether biosignature gases, surface signatures, or seasonal variability of atmospheric gases are present. Atmospheric gases will likely be the most readily detectable biosignatures, but for the very best targets, additional observations to search for surface reflectivity signatures, or to search for seasonal variations in gases (Olson et al., 2018), may be attempted to assess any biosignatures detected (or not detected) in the context of observational discriminants for potential false positives (false negatives) that are present in the planetary environment.

An alternative approach to the assessment of an individual planet for habitability and life would be a statistical approach that looks at particular properties that are more readily observable, such as the presence of CO_2 in the planetary atmosphere and attempts to make that observation for a number of different planets as a function of other parameters such as orbital distance and stellar type. This technique could be used to make an initial observational test for the location of the habitable zone by determining when and where exoplanet terrestrial atmospheres become dominated by CO_2 (e.g., Bean et al., 2017). Similarly, thermal phase curves could potentially identify those planets that lack an atmosphere, providing insight into the persistence of atmospheres on planets orbiting M dwarfs.

Ultimately, the assessment of whether or not a planet is habitable will need to be embedded in the context of the outcomes of terrestrial exoplanet evolution, and so it is critically important to also gather information on planets that are not likely to be habitable—for example, exo-Venuses—to better understand the range of atmospheric compositions expected. Of particular interest are the observationally accessible close-in M-dwarf planets (e.g., GJ1132b; Berta-Thompson et al., 2015) that may have experienced ocean loss and could exhibit an O_2-dominated atmosphere (Luger and Barnes, 2015; Schaefer et al., 2016). Systems containing multiple terrestrial planets will provide an excellent opportunity to compare the evolutionary outcomes at a range of irradiations.

Exoplanet habitability studies will benefit from knowledge of processes and characteristics observed in the Solar System's terrestrial planets, such as atmospheric loss processes on Mars, and ocean loss and catalytic photochemistry on Venus. Understanding terrestrial planet evolution from the Solar System perspective will likely play a crucial role to identify processes that affect habitability.

Developing Complementary Facilities to Characterize Potentially Habitable Planets

Many of the above measurements are extremely challenging, and the number of different types of stellar and planetary characteristics that impact habitability and biosignature detection speaks to developing a complementary approach using multiple techniques and instruments.

For the M-dwarf opportunity, target selection for potentially habitable planets will include several targets already known, including TRAPPIST-1 (Gillon et al., 2017), LHS1140 (Dittmann et al., 2017), and Proxima Centauri b (Anglada-Escudé et al., 2016), as well as a number of planets expected from TESS (Sullivan et al., 2015), and ground-based transit and RV searches. The planets orbiting Sun-like stars that will be studied by direct imaging missions could be discovered by the EPRV or astrometric methods, or discovered by the missions themselves; either way, advanced EPRV or astrometry will be essential to measure the masses of the directly imaged planets.

JWST will likely obtain transmission spectroscopy, secondary eclipse, or phase curves on promising M-dwarfs targets to first establish the presence of an atmosphere, and then proceed to rudimentary atmospheric composition, planetary temperature, and possibly day-night temperature difference (Morley et al., 2017; Lustig-Yaeger et al., 2017; Kreidberg and Loeb, 2016; Meadows et al., 2018). Transmission spectroscopy does not probe to the planetary surface. Hence, it will not be as sensitive to water vapor as direct imaging observations, but it is more sensitive to trace gases in the stratosphere due to the longer slant path. Although these observations will be challenging, they will provide one of the first chances to observe habitable zone planets at infrared wavelengths.

High-resolution spectroscopy, coupled with transit or extreme adaptive optics (ExAO) and coronagraphy, will use transmission spectroscopy (Rodler and Lopez-Morales, 2014), or the radial velocity of reflected light from the exoplanet, to shift exoplanet absorption away from absorption by similar molecules in Earth's atmosphere (Snellen et al., 2015). The search for of O_2 and CH_4 in the atmosphere of Proxima Centauri b may be possible in the next 5 years with the VLT using these techniques (Lovis et al., 2017), and the GSMTs may be able to perform similar observations for several other nearby M-dwarf planets. Mid-infrared direct imaging with GSMTs may detect warm exoplanets orbiting very nearby Sun-like stars, providing information on planetary temperature and complementing direct imaging observations with space-based telescopes.

A direct imaging mission promises the most capability for habitability and biosignature searches of habitable zone terrestrial planets orbiting FGKM stars from ultraviolet to near-infrared wavelengths. Direct imaging can probe to the planetary surface and so is more definitive for habitability detection than transmission, which cannot probe the near-surface atmospheres. Consequently, direct imaging is more sensitive to lower atmosphere water vapor and surface-generated biosignatures. Direct imaging will potentially enable atmosphere detection, atmospheric composition determination (including the deep atmosphere), surface mapping for rotation and obliquity, detection of surface inhomogeneity (or not), detection of ocean glint, and a broad survey of greenhouse gases for FGK stars.

The significant interdisciplinary work described in Chapter 3 will be needed to underpin target selection, measurement requirements, data analysis, spectral retrieval and habitability, and biosignature assessment will be optimally implemented via broad interdisciplinary collaboration, which can be enabled via the mechanisms described in the following section.

MECHANISMS TO ACHIEVE INTERDISCIPLINARITY

As described in Chapters 3 and 4, the study of exoplanets requires a strongly interdisciplinary approach. The detection of exoplanets has been undertaken within the field of observational astronomy, but researchers are now moving into a new era where the characterization and interpretation of data on exoplanet environments will require an interdisciplinary synthesis of observations, computer modeling, data from the Sun and Solar System, and laboratory measurements. This is especially true of studies of terrestrial exoplanets that aim to identify signs of habitability and life, where observations and interpretations of these secondary atmospheres will require expertise from both observational astronomy and many of the Solar System planetary sciences, including terrestrial geophysics, geochemistry, photochemistry and atmospheric science, heliophysics, and Earth science and biology.

Consequently, mechanisms to encourage research endeavors that span and interconnect these disciplines should be strongly encouraged. At NASA, research within the Science Mission Directorate is stove-piped into four divisions: Astrophysics, Planetary Science, Heliophysics, and Earth Science. The Exoplanets Research Program (XRP) is jointly funded by the Astrophysics and Planetary Science Divisions, allowing scientific cross-collaboration between these two communities. The NASA Astrobiology Program, run out of the Planetary Science Division, includes but is not limited to the NASA

Astrobiology Institute (NAI), and this program has fostered interdisciplinary collaboration and cooperation, including some work on exoplanet habitability and biosignatures. The NASA Astrobiology Institute helped to build the astrobiology community by funding large, interdisciplinary research efforts and encouraging teams to collaborate with one another.

NASA recently implemented a new interdisciplinary and cross-divisional research coordination network, the Nexus for Exoplanet Systems Science (NExSS). NExSS was conceived as a large-scale experiment in managing and catalyzing exoplanetary science that integrates the astronomical, terrestrial, planetary, and heliophysical sciences. NExSS is intended to inform and enhance science from upcoming NASA missions such as TESS, JWST, and the potential future LUVOIR, HabEx, and OST telescope concepts that could be used to search for signs of habitability and life on exoplanets. The NExSS research coordination network connects and leverages research from several research and analysis competitions (with awards of different sizes from NAI-scale large collaborative groups to individual PI research in the XRP program) across cooperating NASA divisions, breaking down interdisciplinary and interdivisional barriers to engage in systems science study of exoplanets. One of its key measures of success will be how well it integrates the larger scientific community into its activities. Unfortunately, there is a perception in the community of exclusivity because it is unclear how teams have been chosen to participate, and there has never been a call for proposals to participate explicitly in NExSS.

NExSS has facilitated new, community-inclusive activities and products that transcend the output of the constituent research teams. These NExSS-led activities include the Upstairs-Downstairs Workshop (2016) on the impact of terrestrial planet interiors on planetary atmospheric and surface conditions, essentially working to understand the formation and nature of secondary outgassed atmospheres, which was jointly supported by the NAI and NSF; the Exoplanet Biosignatures Workshop (2016), which produced six community scientific publications that greatly advanced understanding of the significance of false positives and agnostic biosignatures, and fostered the development of the comprehensive framework for biosignature assessment (Kiang et al., 2018; Schwieterman et al., 2018; Meadows et al., 2018; Catling et al., 2018; Walker et al., 2018; Fujii et al., 2018); the Habitable Worlds 2017: A System Science Workshop, which had over 150 attendees as well as webcasting, and strong participation from Earth scientists, planetary scientists and heliophysicists, in addition to astronomers and exoplanet scientists. A NExSS-led community group developed a Laboratory Astrophysics Gap List of needed laboratory studies to be able to interpret exoplanet spectra (Fortney et al., 2016), and mobilized and coordinated the community to contribute numerous white papers to both the NAS Astrobiology and NAS Exoplanet studies. NExSS PIs and their collaborators also contributed to plans for utilization of current space telescopes by bringing together the U.S. and international research communities (in almost equal numbers) to win 23 percent of JWST Early Release Science. These proposals will provide the initial characterization of JWST performance for studies of exoplanets, and will provide the first steps toward habitable zone planet characterization and biosignature searches.

> **Finding:** The search for life outside the Solar System is a fundamentally interdisciplinary endeavor. The Nexus for Exoplanet Systems Science (NExSS) research coordination network encourages the cross-disciplinary and cross-divisional collaborations needed to support NASA exoplanet research and missions.

However, NExSS is currently comprised of research efforts funded via other programs at NASA and has very modest funding of its own; sufficient to cover only community activities like workshops and conferences. This model is not optimal for selecting proposals that are closely aligned with NExSS goals, as the teams selected need, first and foremost, to be responsive to the particular call under which they were funded, and responsiveness to NExSS goals is not a criterion for selection in the parent funding program. Additionally, without a NExSS-specific call for participation, teams have been selected from different relevant programs in a process that is not as transparent as an open call, although PIs now have the option to self-select membership into NExSS for the NASA Exobiology and Habitable Worlds programs. Consequently, the NExSS research coordination networks would be strengthened by the provision of program status, with sufficient funding to enable open competitive selection of teams funded directly by the NExSS program.

> **Recommendation: Building on the NExSS model, NASA should support a cross-divisional exoplanet research coordination network that includes additional membership opportunities via dedicated proposal calls for interdisciplinary research.**

REDUCING BARRIERS TO SCIENTIFIC EXCELLENCE

The committee was charged with surveying the status of the field of exoplanet science (see charge in Appendix A), and no such survey would be complete without consideration of the state of the field's workforce. The search for life on other worlds is both a profound and a profoundly difficult endeavor. Maximizing excellence and ensuring success of exoplanet science depends on marshaling, developing, and supporting all available talent. As a growing field, exoplanetary astronomy is particularly dependent on the effective development and retention of junior scientists because it is now putting into place the cohort that will provide senior leadership for many decades.

While studies have not been published specifically for the field of exoplanets, the committee has examined recent reports that provide evidence of systemic barriers in in science, technology, engineering, and mathematics (STEM) fields including astronomy. The Exoplanet Science Strategy, therefore, includes a strategy for developing and maintaining human capital, including addressing demographics and standards of professional conduct, and identifies areas requiring further research.

Equity and Inclusion

Several recent reports provide evidence that women and people of color are underrepresented in the professional astronomy workforce. Only 26 percent of all members are female and just 5.3 percent are members of underrepresented minority groups (URMs[10]).[11] Over the last 10 years, women earned approximately 32 percent of the PhDs in astronomy, and this number has been essentially flat over that period.[12] According to a recent study, perceived discrimination in a field significantly deters women from choosing that course of study in university (Ganley et al., 2017). In 2013, women in astronomy comprised 26 percent of assistant professors, 19 percent of associate professors, and 14 percent of full professors (Hughes, 2014).

Concrete recommendations on how to address this underrepresentation can be found in three studies highlighted here. The report of the 2015 Inclusive Astronomy (Nashville) Conference (hereafter referred to as IA2015), endorsed by the U.S. American Astrological Society (AAS), analyzes current barriers to access for URMs in astronomy and provides a wide-ranging set of recommendations for removing them.[13] The National Academies recent report titled, *Sexual Harassment of Women: Climate, Culture, and Consequences in Academic Sciences, Engineering, and Medicine* (hereafter referred to as SHW2018) lists evidence-based practices to achieve gender parity, most of which come from the substantial research NSF has funded through its ADVANCE program.[14] The Best Practices Guide of the

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[10] URMs are defined in this report as Hispanic or Latino, Black or African American, American Indian or Alaska Native, or Native Hawaiian or other Pacific Islander.

[11] 2016 AAS Workforce Study; see https://aas.org/files/aas_members_workforce_survey.pdf

[12] See https://www.aip.org/statistics/data-graphics/percent-bachelors-degrees-and-doctorates-astronomy-earned-women-classes.

[13] See https://tiki.aas.org/tiki-index.php?page=Inclusive_Astronomy_The_Nashville_Recommendations.

[14] See https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5383.

AAS Committee for Sexual-Orientation and Gender Minorities in Astronomy provides ways to improve the climate for LGBT+ scientists, who are also marginalized, that apply to improving equity and inclusion for all.[15]

Adopting the recommendations presented by these three reports are important first steps toward addressing the barriers raised by homogeneity, bias, harassment, and discrimination in the astrophysics and planetary science workforce.[16] The committee therefore fully endorses those recommendations.

Harassment

The AAS Code of Ethics defines harassment as "behaviors that, if engaged in because of race, religion, color, gender, age, national origin, disability, marital status, sexual orientation, gender identity expression, or any other protected class, may give rise to a hostile work environment," and the committee adopts this definition here.[17]

SHW2018 reports that, "In the best meta-analysis to date on sexual harassment prevalence, Ilies and colleagues (2003) reveal that 58 percent of female academic faculty and staff experienced sexual harassment." Although SHW2018 does not deal with other forms of harassment, it recognizes that "women who have multiple marginalities … experience certain kinds of harassment at greater rates than other women." The Clancy et al. (2017) survey of 474 astronomers and planetary scientists found that "39 percent of respondents report experiencing verbal harassment at their current position, and 9 percent report experiencing physical harassment" while also reporting that, "women of color experienced the most hostile environment."

SHW2018 notes that male-dominated organizations are more likely to have sexual harassment within them so that "Two important steps in correcting this problem are achieving critical masses of women at every level and changing policies and practices that are impeding the ability for women to enter and advance in academia." It goes on to say, "Gender parity, specifically among faculty, is especially important, given that faculty lead and set the tone in labs, medical teams, classrooms, departments, and schools."

New codes of ethics of professional societies, including the AAS, reflect a broad realization that unethical environments prevent scientific excellence. The American Geophysical Union (AGU)'s 2017 Scientific Integrity and Professional Ethics Policy recognizes harassment as a form of scientific misconduct, as does the SHW2018 report, which then goes on to recommend that institutions "Move beyond legal compliance to address culture and climate."

> **FINDING:** To maximize scientific potential and opportunities for excellence, institutions and organizations can enable full participation by a diverse workforce by taking concrete steps to eliminate discrimination and harassment and to proactively recruit and retain scientists from underrepresented groups.

In society at large, retaliation against complainants is common.[18] SHW2018 notes that fear of retaliation and negative career outcomes prevent women from reporting harassment and recommends that funders, such as NASA and NSF, support research into mechanisms for protecting targets from retaliation. This committee endorses the SHW2018 finding that, "Systems and policies that support

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[15] See https://sgma.aas.org/sites/sgma.aas.org/files/LGBTInclusivityPhysicsAstronomy-BestPracticesGuide2ndEdn_small.pdf.

[16] See Chapter 6 in SHW2018.

[17] See https://aas.org/ethics#bullying.

[18] See http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.518.3744&rep=rep1&type=pdf and https://www.eeoc.gov/eeoc/statistics/enforcement/.

targets of sexual harassment and provide options for informal and formal reporting can reduce the reluctance to report harassment as well as reduce the harm sexual harassment can cause the target."

As SHW2018 finds, when reporting systems are not comprehensive, well-advertised, and used to solve problems, informal 'whisper networks' "are used to warn women away from particular programs, labs, or advisors," which "automatically [reduces women's] options and chances for career success."[19] Such networks also exist among other underrepresented groups. Furthermore, "Confidentiality agreements in settlements [can] shield harassment cases from view and make it possible for perpetrators to seek new jobs and keep problems secret" (Cantalupo and Kidder, 2017).

Discrimination and pervasive harassment within the greater scientific workforce likely affect the exoplanet community and serve as barriers to the participation of people from certain demographic groups. SHW2018 cites many studies to show that harassment causes scientists to be less productive and leave their jobs. This committee wants junior scientists to find the exoplanet field hospitable and to continue to contribute their talents to it.

Areas Needing Further Research

A variety of approaches to education and remediation may reduce harassment, discrimination, and other forms of abuse, not limited to illegal behavior. The committee suggests that the following areas merit further study:

1. Research into the most effective professional sanctions for different forms of abuse. SHW2018 recommends that academic institutions could consider a range of disciplinary actions.
2. Mechanisms to destigmatize reporting. IA2015 recommends that the astronomical community "create and highly publicize a robust reporting procedure to address all relevant dimensions of identity and social experience." Such publicity might encourage reporting of incidents for which education may be a more appropriate response than punitive sanctions. Lowering the perceived bar for reporting problems may generate additional constructive opportunities for change, while increasing the likelihood that patterns of problematic behavior will be reported.
3. Training of numerous people within academia to provide support and resources to victims of harassment and discrimination, including advice both about how to stop or report the abuse and about the career implications of reporting. The number of trained people required to meet this need without posing an undue burden on each individual merits evaluation.
4. Demographic and climate surveys that reveal problems that may limit an institution's success at recruiting and supporting a diverse workforce and track the efficacy of newly implemented procedures. Surveys should be evaluated by people who appreciate barriers to survey completion, particularly for members of groups whose identities can readily be discerned.
5. Examination of telescope and agency funding allocation processes for bias. For example, Space Telescope Science Institute analyzed Hubble Space Telescope proposals and found that male PIs had a higher success rate (Reid 2014).
6. Development of leadership training programs. SHW2018 particularly emphasized the importance of strong leadership for setting cultural standards. Leaders have the power and responsibility to build a culture of inclusivity within their group, department, or organization.

This list is not intended to be comprehensive, and the committee recognizes that a panel dedicated to studying workforce development may identify additional important items.

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[19] SHW2018 cites http://www.newsweek.com/what-whisper-network-sexual-misconduct-allegations-719009.

Decadal Survey Endorsement

IA2015 recommended that all stakeholders, including policy makers and funding agencies "act proactively as well as reactively," not "wait for a problem to arise to attempt to fix it." It lists actions that can be taken by funding agencies to remove barriers to access and create inclusive environments with effective leaders.[20]

> **FINDING:** Development and dissemination of concrete recommendations to improve equity and inclusion and combat discrimination and harassment would be valuable for building the creative, interdisciplinary teams needed to maximize progress in exoplanet science over the coming decades.

The committee endorses the IA2015 recommendation that, "The decadal survey should address issues of policy making and leadership diversity imbalances as recommendations that can be acted upon by policy makers." To achieve this goal, the Astronomy and Astrophysics and the Planetary Science Decadal Surveys will need to consult with experts beyond the astrophysics and planetary science communities and with members of underrepresented and marginalized groups.

As the exoplanet community continues to research and implement the recommendations cited above, these efforts will enable a diverse and productive cohort of scientists to accomplish the exciting, interdisciplinary, and profound goals of this report.

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5

Opportunities for Coordination between Organizations and for Cooperation with Industrial and International Partners

The international exoplanet research landscape is very vibrant, as amply demonstrated by very successful past collaborations. Excellent future collaboration opportunities include utilization of existing and future instrumentation and technology development. For example, very successful collaborations between NASA and the European Space Agency (ESA), as well as the space agencies of individual countries, exist for many of the largest astrophysical facilities, including the Hubble Space Telescope (HST) and the James Webb Space Telescope (JWST). As another example, Europe has played an important role in the exploitation of the Kepler and K2 mission data using ground-based telescopes.

Similarly, collaborations between industrial partners and government agencies have proven essential in enabling several missions. Several industrial partners have also been actively involved in NASA's four large mission concept studies for the next decadal survey.

In the light of the first recommendation of this committee for NASA to lead a direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars, and the undoubtedly significant cost, long lead-time, and technical complexity of such a project, collaboration with foreign space agencies and associated exoplanet scientists and engineers is a logical path, and may be a necessary path. From a scientific point of view, there is already great enthusiasm in both Europe and Asia to potentially participate in such a mission.

Ground-based instrumentation is a strong point of European astronomy, and exoplanet science in particular. Just as with Kepler and K2, the NASA Transiting Exoplanet Survey Satellite (TESS) mission will strongly benefit from the supporting radial velocity follow-up observations with the dedicated radial velocity machines such as High Accuracy Radial Velocity Planet Searcher (HARPS), HARPS-N (and HARPS-3, under development), Calar Alto High-Resolution Search for M Dwarfs with Exoearths with Near-Infrared and Optical Échelle Spectrographs (CARMENES), Fiber-Fed Échelle Spectrograph (FIES), and the recently commissioned Échelle Spectrograph for Rocky Exoplanet- and Stable Spectroscopic Observations (ESPRESSO). In fact, the committee stresses here that coordination between all the different parties, in conjunction with the national radial velocity (RV) machinery, is key to avoid unnecessary duplication and consumption of valuable resources.

As the committee recommends that the National Science Foundation (NSF) invest in both the Giant Magellan Telescope (GMT) and Thirty Meter Telescope (TMT) and their exoplanet instrumentation, it also notes that important synergies in technology development with the European Extremely Large Telescope (ELT) are likely and will be beneficial. The ELT is fully funded and under construction, and the first-light instrument Mid-Infrared E-ELT Imager and Spectrograph (METIS), a mid-infrared high-dispersion Integral Field Unit (IFU) spectrograph and imager, is specifically designed for characterization of thermal emission of exoplanets. One of the great promises of giant segmented mirror telescope (GSMT) science is probing molecular oxygen in the transmission and reflected-light spectra of temperate terrestrial planets, requiring optical high-dispersion spectroscopy, and in the case of reflected-light studies in combination with high-contrast imaging. For all telescope projects, such instrumentation still has a long lead-time, needing significant technology development (such as making extreme adaptive optics work in the optical). Therefore, it would strongly benefit from development of optimized coronagraphs coupled to high-dispersion spectrographs, and would strongly benefit from open sharing of technology and ideas, with the aim to significantly expedite their deployment on the GSMTs.

Private foundations have become increasingly active in supporting exoplanet and related science since the last decadal survey. Examples include the Breakthrough Initiative, which funds a number of efforts centered on the search for extraterrestrial intelligence, the 51 Pegasi b Postdoctoral Fellowship funded by the Heising-Simons Foundation, and the astrobiology-focused Collaboration on the Origins of Life funded by the Simons Foundation. Currently, these initiatives mostly set their own agendas without coordinating with each other or national bodies, which has both advantages and disadvantages. The advantages are that private foundations can be nimble and respond quickly to emerging opportunities and also fund riskier projects that require preliminary data to demonstrate their efficacy. On the other hand, the lack of coordination can lead to duplication of effort or the support of projects that do not advance the field's primary strategic objectives. Better communication between foundations and government agencies, and the consideration by private foundations of the strategic plan in this report and in the National Academies of Sciences Astrophysics and Planetary Science decadal survey reports, would reduce the disadvantages of private funding while maintaining most of the advantages.

The GMT and TMT projects have also enjoyed substantial private investment, both directly from philanthropic individuals and foundations and through the participation of private universities. This investment has helped advance the design of the telescopes and instruments and also retire key risks (e.g., the casting and polishing of the off-axis mirrors for the GMT primary). Nevertheless, it is clear that private funding alone cannot bring these projects to fruition. U.S. federal funding is essential for these projects to succeed and, as described elsewhere in this report, the exoplanet science that they would enable is exceptionally compelling. Thus, the recent collaboration of the GMT and TMT organizations with the NSF (through National Optical Astronomy Observation [NOAO]) to articulate a community-based science program for presentation to the next decadal survey is a welcome development. Continuation of this public/private partnership is perhaps the best chance for realizing the ambitious program of ground-based exoplanet science outlined in this report.

As is evidenced by many of the recommendations in this report, as fields of study mature, the scope of the scientific questions that are being addressed increases, the complexity and cost of instruments, telescopes, and missions continue to correspondingly increase. At some point, these endeavors become too large to be affordable, built, and maintained by any single agency, university, company, or even country. One obvious example of this is in the field of particle physics with the Large Hadron Collider, a project undertaken by a large collaboration of scientists, universities, and countries. The field of exoplanets has now reached the maturity and ambition that answering some its most profound questions—notably, "Does life exist on planets orbiting other stars?"—requires projects that are likely too large to be realistically accomplished by any single entity. Nevertheless, there are often institutional barriers to forming partnerships between various agencies or organizations, which slow the pace of the field and hinder the progress of the scientific community in advancing its knowledge of these big questions.

> **Finding:** By continuing to find novel ways of partnering with each other, and by removing or reducing institutional barriers to such partnerships, agencies may be able to better address some of the most profound scientific questions outlined in this study, which often require instruments, telescopes, or missions that are too ambitious or expensive for any individual agency to fund, build, and operate alone.

6

Timeline for the Exoplanet Science Strategy

The exoplanet community aims to accomplish the parallel goals of increasing understanding of planetary systems as astrophysical objects and taking the next steps toward identifying habitable environments and biosignatures on extrasolar worlds. This chapter summarizes and restates the strategy envisioned by the Exoplanet Strategy Committee, separated here into near-term (< 5 years), medium-term (5-15 years), and long-term (15-20 years) goals.

NEAR-TERM ACTIVITIES

The field of exoplanet science is relatively new and remains a vibrant and evolving research area. In the near term time scale (<5 years) and extended forward into the mid-term, support for innovative ideas in theory, observations, and instrumentation is needed. Exoplanet science is also an increasingly and necessarily interdisciplinary endeavor, spanning both astrophysics and planetary science, and currently in particular need of substantial input from stellar astrophysics and laboratory studies. Support in the form of consistently well-supported individual investigator grant programs, including opportunities for technology development, theoretical work, and interdisciplinary collaboration, is needed to maximize the yield of strategic programs in exoplanet science.

The James Webb Space Telescope (JWST) has the potential to provide infrared spectra of terrestrial-size planets in and near the liquid water habitable zones of M dwarfs, as well as a statistical sample of spectra for up to about 100 larger and hotter planets. The latter will enable the search for physical and chemical trends across objects, while the former will significantly advance understanding of planetary habitability. The spectra of warm terrestrials will answer the critical question of what kinds of atmospheres rocky planets around M dwarfs can form and retain. In terms of potentially habitable worlds, JWST may have the capability to detect molecules (such as H_2O, CO_2, and CH_4, although most likely not O_2) in the atmospheres of a handful of the most favorable planets. However, the precise outcome of JWST investigations in this area hinges on several unknown factors, including the noise floor of its instruments, the number of potentially habitable worlds that will be discovered around late M dwarfs within 10 pc by the Transiting Exoplanet Survey Satellite (TESS) and other surveys, the nature of these planets' atmospheres, and the community's willingness to invest hundreds of hours of observing time on individual planets.

Given the limited lifetime of JWST and the substantial interest in observing time from scientists across all areas of astrophysics and planetary science, the exoplanet spectroscopy work should be conducted as efficiently as is possible with full community involvement. JWST's current launch timeline means that many ideal atmospheric characterization targets will have been discovered by TESS in advance of launch. The committee recommends that NASA create a mechanism for community-driven legacy surveys early in the JWST mission that would allow exoplanet astronomers to self-organize to propose a survey of atmospheres that would benefit the full community.

Current workforce development will affect exoplanet science for years to come. The committee sees a need for current action to improve community practices in areas including but not limited to reducing harassment and discrimination on the basis of race, gender, sexual orientation, gender identity, and other marginalized identities, as well as addressing intersectional concerns. The committee considers the Astronomy and Astrophysics and Planetary Science Decadal Surveys to be appropriate venues to convene committees of experts to provide recommendations for improved workforce development.

MEDIUM-TERM ACTIVITIES

The committee identifies several large strategic priorities that must be begun now and will come to fruition in the medium-term time scale of 5-15 years. The committee reaffirms support of the exoplanet community for two major projects currently in progress: the Wide-Field Infrared Survey Telescope (WFIRST) and the U.S.-led giant segmented mirror telescopes (GSMTs: Giant Magellan Telescope [GMT] and Thirty Meter Telescope [TMT]).

Understanding the structure of planetary systems is crucial both to an understanding of planets as astrophysical objects and to the evaluation of potential habitable environments. Current knowledge of exoplanet occurrence rates shows that Earth-size planets are common enough in the Solar System neighborhood to plan for their atmospheric characterization. However, this information does not show the histories or formation contexts of these bodies. Fundamentally, systems like the Solar System remain largely inaccessible to current detection techniques, and it is still not known whether this system architecture is common or rare. Planet statistical demographics from Kepler have launched a reimagining of planet formation scenarios. Information about planets in a new phase space—one that encompasses solar-system-like architectures—would do the same. The committee thus endorses the WFIRST microlensing survey. This survey will substantially broaden the view of the structures of planetary systems and their diversity as well as the range of physical processes that determine planet compositions. The committee notes that Solar System bodies are a touchstone for understanding of physical planet properties, so evaluation of potential biosignatures on exoplanets will rely on a clear understanding of how the Solar System's properties compare to those of other systems. The WFIRST microlensing survey is thus important for both primary goals of this report. The committee further supports flying the WFIRST coronagraph and demonstrating its capabilities on exoplanet targets, both a technology demonstration on the path to future missions capable of imaging terrestrial exoplanets, and to place tighter constraints on the typical levels of exozodiacal light, which will affect the capabilities of such missions.

The 3-fold improvement in angular resolution, 10-fold improvement in light-collecting capabilities, and 80-fold improvement in sensitivity to point sources provided by the next generation of GSMTs will open up new vistas of exoplanet exploration. From the detection and spectroscopic study of gas and ice giants in reflected light and thermal emission, to the search for biosignatures of rocky planets orbiting M dwarfs, direct imaging and high-resolution spectroscopy on GSMTs will be capable of spectroscopically characterizing transiting and nontransiting exoplanets. The committee notes here the particular synergy of the GSMTs (which could detect O_2 in the atmospheres of several temperate terrestrial planets) and JWST (which likely cannot detect O_2, but could detect other gases such as H_2O, CO_2, and CH_4, which are essential to evaluating whether the oxygen is biogenic).

While many small-scale efforts are best supported by openly advertised, competitive individual investigator opportunities, the committee finds one particular area in need of strategic investment from now through the mid-term time scale. Mass is a fundamental planetary property, necessary to understand bulk compositions and system architectures as well as to interpret atmospheric spectra. The committee finds that radial velocity measurement is the technique most likely to provide masses for a substantial number of Neptune, super-Earth, and terrestrial-mass planets. However, the success of efforts to improve radial velocity precision to the required level is not assured. In addition to improvements in instrument capabilities, the varied velocity signals produced by surface processes on stars will need to be understood at a substantially better level. The committee considers this problem too large to be addressed by principal investigators (PIs) in possession of individual investigator grants and thus recommends that NASA and the NSF establish an extreme precision radial velocity initiative to support and organize these efforts in order to maximize the science yield of future missions and the GSMTs. The committee emphasizes that a single co-located center is not recommended for this endeavor. Rather, the varied expertise of investigators at a range of institutions will be needed. The committee suggests that progress in precision measurement of masses through the radial velocity (RV) technique would benefit from NASA's established ability to organize large groups of investigators in pursuit of demanding, unprecedented, and clearly defined goals.

LONG-TERM ACTIVITIES

Direct imaging of exoplanets requires angularly resolving the planets from their host stars and directly detecting photons from the planets. Separating the planet's image from its host star is fundamentally limited by the theoretical diffraction limit, which is set by the observing wavelength and the telescope diameter. The large flux ratios and small angular separations imply that directly imaging and spectroscopically characterizing planets close to their host star requires dedicated high-contrast facilities, which is where the committee sets its sights for the long-term time scale (15-20 years from now).

Lynx

An X-ray mission such as Lynx would provide information about the high-energy radiation and stellar wind fluxes received by planets from their host stars. These stellar inputs are important for understanding atmospheric escape, evolution, and photochemistry. The committee considers this science interesting but finds that, unlike the other three proposed missions, this science case does not address the currently most central questions in exoplanet science.

OST

A cooled near-to-far infrared (IR) mission such as the Origins Space Telescope (OST) would advance exoplanet science both by providing inputs to the study of planet formation through investigations of protoplanetary disks and by allowing planetary atmospheric characterization via the transit method. For the study of protoplanetary disks, the committee considers such a mission to be potentially transformative given its far-IR coverage. High spectral resolution investigation of water lines would allow study of the spatial distribution of water across disks. Measurements of hydrogen deuteride (HD) lines would allow direct measurement of hydrogen masses of disks. Both would provide important information about the conditions under which planets form.

For the direct study of exoplanets, OST's primary strength is in atmospheric characterization through transit spectroscopy in both primary and secondary eclipse. Like JWST, OST's mid-IR wavelength coverage allows secondary eclipse measurements to probe thermal emission from temperate atmospheres and detect a variety of key molecules using transmission and emission spectroscopy. Given sensitivity constraints, OST would be able to characterize terrestrial-size planets in the liquid water habitable zone around mid- to late M-dwarfs but not around earlier-type stars, including Sun-like stars.

The committee finds that OST will likely provide only a modest increase in the number of habitable zone M-dwarf exoplanets that can be characterized compared to JWST. The currently proposed aperture, spectral resolution, and wavelength coverage of OST do not differ substantially from JWST, and thus improvements over JWST in OST's ability to characterize atmospheres are primarily predicated on an improved instrumental noise floor. Since detector stability for transit spectroscopy was not a technology driver for JWST's design, such an improvement is plausible, but not guaranteed.

The committee is excited about exploring the atmospheres of terrestrial planets in the habitable zones of M dwarfs. These planets may host life and, given the large of abundance of M dwarfs, may even be the most common habitable environments. However, the committee has reservations about currently investing in an OST-like mission for the purposes of exoplanet science given its potentially modest improvement in atmospheric characterization when compared with JWST. In addition, the habitable zone of M dwarfs might not in fact be a habitable environment given its extreme exposure to high-energy stellar irradiation. Observations by JWST will address whether terrestrial planet atmospheres can survive under these conditions. Earth-like orbits around Sun-like stars need not be the only habitable environments, but Earth's biosphere provides the only known example of a place where life can arise. OST would not open up the significant discovery space to characterize Earth-like planets around more Sun-like stars.

HabEx and LUVOIR

The committee considers a large space-based, direct imaging mission, capable of directly detecting and characterizing terrestrial planets in reflected light around Sun-like stars at near-ultraviolet, optical, and near-infrared wavelengths, to be the primary long-term priority for NASA exoplanet science. Such a mission would explore the atmospheres of planets with a range of sizes and effective temperatures, and image multiple planets in each system, enabling comparative exoplanetology. A direct imaging mission would also be sensitive to terrestrial planets in the habitable zones of stars similar to the Sun, environments for which Earth provides a proof of concept that habitability is possible, but which are accessible only from space.

Measurements over the past decade have dramatically reduced three major risk factors identified in the 2010 Astronomy and Astrophysics Decadal Survey for a planet-imaging mission. First, abundance statistics from Kepler strongly suggest that terrestrial planets are common in the habitable zones of stars similar to the Sun. Second, Large Binocular Telescope Interferometer (LBTI) measurements and upper limits for exozodiacal dust in habitable zones indicate that dust is unlikely to prevent optical characterization of planets in most systems. Finally, coronagraph and starshade technologies have advanced substantially, and designing starlight suppression systems that perform at levels necessary for an imaging mission is now practical.

Molecular features of interest for atmospheric characterization are present from the UV to mid-IR, and which features are the best probes of atmospheric physics and chemistry will depend on what properties of planetary atmospheres turn out to be most common. For planets orbiting more Sun-like stars using direct imaging, the UV to near-IR wavelength range is the most accessible. This region is promising for identifying biosignature gases because it hosts multiple features of molecular oxygen (0.2, 0.69, 0.76, and 1.27 microns; see Table D.1 in Appendix D), as well as its photochemically produced by-product ozone (0.2-0.3 and 0.5-0.7 microns) and collisionally induced O_2 absorption in atmospheric pressures higher than Earth's (0.3-1.27 microns). In the past 5 years, astrobiologists have developed and improved the understanding of how to more credibly interpret potential biosignatures in the context of their planetary and stellar environments, and O_2 is the best studied example for this paradigm. The assessment of an O_2 detection as a biosignature will be strengthened by searching for observational discriminants that can systematically rule out abiotic mechanisms that could also form it and searching for other environmental characteristics, such as the simultaneous presence of CH_4 or N_2O that could make the biological interpretation more credible. Features of one such disequilibrium partner—namely, CH_4—are present at 0.79 microns and longer, making them potentially accessible to an optical mission depending on atmospheric concentrations (although the strongest methane features are in the near- and mid-IR). False positive complements to molecular oxygen, such as carbon dioxide, carbon monoxide, and absorption from oxygen collisions, which in large abundances may suggest oxygen production through photolysis or photochemistry, also have features at wavelengths shorter than 1.8 microns (see Appendix D).

The committee acknowledges that this focus on molecular oxygen may well be an Earth-centric view of biosignatures and the properties of life on other worlds, but as researchers embark on this journey of exploration, the committee considers oxygen, with its disequilibrium complements methane (possible to detect concurrently given some mission architectures) and nitrous oxide (available only with follow-up observations at wavelengths longer than 2.1 microns), a compelling place to start.

When evaluating the science potential of proposed optical imagers, several capabilities must be considered.

Aperture

The primary benefit of a larger aperture telescope is that, in general, it allows characterization of planets orbiting stars at larger distances from the Sun, increasing the sample of accessible objects. How many objects are needed for transformative science?

For Neptune and Jupiter-size planets, several atmospheres have already been characterized and a statistical sample is needed. Hot Jupiter atmospheric characterization shows that, even in the case of these hydrogen- and helium-dominated planets, a sample of 10 objects contains substantial spectral diversity and is not enough objects to derive statistically significant trends that explain their physical and chemical differences. Of order 50 objects or more would be needed to improve this understanding. If multiple planets are imaged in the same system, however, a smaller sample of giants would become interesting. Currently, only the directly imaged system HR 8799 contains multiple planets for which concurrent atmospheric characterization is possible. A sample of more than several systems with multiple characterized planets would enable tests of planet formation by allowing comparison of atmospheric compositions at a range of orbital distances.

For super-Earth-size planets, less information is currently available than for giants, and a sample of at least 10 would be illuminating. A substantially better physical understanding would likely result from a larger sample containing several objects both smaller and larger than the radius valley at about 1.8 times the radius of Earth which has been measured for short-period planets, as well as objects on orbits with periods greater than 25 days, which are less likely to be affected by atmospheric evaporation than their short-period brethren. Given current estimates of the occurrence rates of hot, warm, and cold super-Earths, Neptunes, and gas giants, both HabEx and LUVOIR will be able to detect and characterize several hundred such planets, thus yielding a statistically significant sample of planets with which to perform, for the first time, comparative exoplanetology over a broad range of planet masses and temperatures.

The committee concludes that the characterization of the atmospheres of terrestrial planets in the habitable zones of Sun-like stars is the most compelling opportunity in the field of exoplanets. The current knowledge of terrestrial planet occurrence rates indicates that targets for such characterization are within reach of technologies under study by the HabEx and LUVOIR Science and Technology Definition Teams (STDTs). However, the modest uncertainties in the occurrence rates and the risk of small number fluctuations requires a conservative approach to designing a mission that can guarantee at least a few terrestrial planet atmospheres. That is, the minimum expected yield for a mission should be on order of 10 terrestrial planet atmospheres to be certain that at least one, and very likely at least a few, will be observed. The committee finds that the HabEx “A” mission concept, as it is scoped at the time of this writing (4 m primary mirror diameter), meets this threshold criterion. Measurements of the atmospheres of a few terrestrial planets would give a first glimpse into the diversity of these worlds and the committee would consider this to be a major advance.

At the same time, the committee has every expectation that the characteristics of a few planets will not be representative of the full class of objects, given the already known diversity of planets in the Solar System and beyond. A mission capable of characterizing a statistical sample of approximately 50 terrestrial planet atmospheres would allow for a thorough exploration of the types of terrestrial atmospheres that exist, enabling dramatically more science. This is particularly critical for the search for evidence of life through biosignatures, where comparative planetology will likely be essential for interpreting detections. The committee finds that the LUVOIR “A” mission concept, as it is scoped at the time of this writing (15 m primary mirror diameter), would enable this ambitious objective.

Wavelength Range

Although oxygen alone is not a definitive biosignature, the committee finds that detection of molecular oxygen in a terrestrial planet's atmosphere would be a monumental discovery, and it would justify significant further observation of the planet's environment to assess the likelihood that the O_2 was biological in origin. Simultaneous detection of molecular oxygen and methane, a disequilibrium pair, would be yet more exciting since this would be a more direct suggestion of atmospheric alteration by life. Detectability of oxygen or methane by a proposed mission will necessarily depend on atmospheric abundances. Earth's complement of oxygen and methane have, for example, varied substantially over time, making exoplanet expectations difficult to impossible to define. Similar atmospheric assumptions should be made when comparing mission architectures.

For the purposes of exoplanetology, a number of molecular features have the potential to be important. In particular, the waveband 0.2-1.8 microns hosts features of O_2, O_3, O_4, CH_4, CO_2, CO, N_2O, H_2, SO_2, H_2O, and features from aerosols such as H_2O, H_2SO_4, and hydrocarbons, and could support surface liquid water detection via phase dependent mapping to search for ocean glint. The waveband 5-20 microns hosts features of O_3, CO_2, CH_4, N_2O, SO_2, and H_2O, and could reveal surface or brightness temperatures. See Appendix D for additional information, including wavelength details, and the role of each molecule as either a biosignature, false positive discriminant, or habitability indicator.

Spectral Resolution

Exoplanet atmosphere studies have demonstrated that low-resolution spectra ($R = 100$) can be interpreted with substantially more confidence than photometric data. Photometric points can be quite valuable for providing baseline information about atmospheric structures, but the committee advises that only resolved wavelength ranges be included when evaluating the potential for missions to identify molecular features.

Field of View

Although a telescope capable of imaging Earths can necessarily image larger planets as well, comparative planetology of a range of objects requires that an imager be sensitive to a range of orbital separations, not solely the habitable zone. Large-separation planets at fixed size and albedo are fainter than their close-in counterparts. A field-of-view large enough to encompass the faintest detectable giant planets for many systems would maximize the planetary yield of an imaging mission.

THE JOURNEY AHEAD

Finding, verifying, and exploring the characteristics of life on other worlds will be a many-step process. The committee recommends balancing a measured, step-by-step strategy that will allow the building of a nuanced understanding of planetary systems with bold steps targeted toward the current fledgling understanding of planetary habitability. Optical imaging of habitable zone terrestrial planets would advance both of these objectives. Planning further major steps in the search for life could be precipitous in this journey of exploration. Researchers do not yet know how strange these newly discovered worlds will be, nor can they predict the diversity of detectable extrasolar life. If the next generation of space telescopes detects a signature of molecular oxygen on a habitable zone terrestrial planet orbiting another star, the race will be on to characterize that planet and its system in as much detail as possible. What is the planet's orbit? What other planets are in the system and what are their properties? What other molecules can be detected in the planet's atmosphere across the widest possible wavelength range? Are disequilibrium gases such as methane also present? In other words, what is the context for that detection of oxygen, and can it be explained only by life?

The committee's Exoplanet Science Strategy affirms that the answer to one of humanity's greatest questions is within reach. For generations, humans have looked up at the stars and wondered whether or not we are alone. We do not know whether our generation will be the first to learn that life exists elsewhere in the galaxy. What we do know is that we can be the first with the technology, the scientific ability, and the sheer unrelenting drive to take the bold steps toward answering that great question. This may be a long journey, but if we choose to embark upon it, we will ultimately find our place in the Cosmos.

Appendixes

A

Statement of Task

In preparation for and as an input to the upcoming decadal surveys in astronomy and astrophysics and planetary science, the National Academies of Sciences, Engineering, and Medicine will appoint an ad hoc committee to perform a study with the following objectives:

- Survey the status of the field of exoplanet science, including the use of current and planned facilities such as Transiting Exoplanet Survey Satellite, the James Webb Space Telescope, the Wide Field InfraRed Survey Telescope, and any other telescope, spacecraft, or instrument, as appropriate.
- Recommend an Exoplanet Science Strategy that outlines the key scientific questions for exoplanet science and research and related near-, medium-, and far-term measurement and technology goals. The Strategy will include the search for life in the universe as well as cross-discipline opportunities in Earth science, astrophysics, heliophysics, and planetary science.
- Discuss which of the key goals of the committee's Strategy could be addressed via current decadal survey recommended priority activities and also identify opportunities for coordination with international partners, commercial partners, and not-for-profit partners.

In the course of conducting this study, the committee will consider and regularly consult with the concurrent study "State of the Science of Astrobiology," in the area of assessing habitability, searching for signs of life, and other relevant areas of scientific overlap. Also the committee will not revisit or redefine the scientific priorities or mission recommendations from previous decadal surveys.

B

White Papers

CALL FOR WHITE PAPERS

Issued by the Committee on an Exoplanet Science Strategy

Dear Colleagues,

In preparation for and as an input to the upcoming decadal surveys in astronomy and astrophysics and planetary science, the National Academies of Sciences, Engineering, and Medicine has been charged with carrying out a study on the science strategy for field of extrasolar planets. The committee's statement of task involves surveying the status of the field, recommending a future science strategy, discussing ways in which the key goals identified by the committee can be addressed by current priorities and activities, and identifying possible opportunities for coordination with international, commercial, and not-for-profit partners. The committee will regularly consult with the concurrent study on the "State of the Science of Astrobiology."

The committee is requesting community input on these topics in the form of white papers. Please find below recommended topics for white papers and submission guidelines. White papers will be accepted from now until March 9, 2018.

Please note that multiple authorship accurately reflecting a consensus among many individuals is strongly encouraged. Everyone in the research communities associated with exoplanets, astrobiology, and related fields is encouraged to author or collaborate on these papers.

Note that the committee will also consider reports from the Program Analysis (PAG) study groups, so these need not be resubmitted as white papers, although any important and relevant updates to these reports are encouraged.

Recommended Topics for White Papers

The following topics, derived from the study's statement of task, are suggested. White papers should not revisit or attempt to redefine the scientific priorities or mission recommendations from previous decadal surveys or strategies:

- Identify areas of significant scientific progress since publication of the New Worlds New Horizons Decadal Survey.
- Identify exoplanet science areas where significant progress will likely be made with current and upcoming observational facilities, such as the Transiting Exoplanet Survey Satellite, the James Webb Space Telescope, the Wide Field InfraRed Survey Telescope, and other ground- and space-based facilities.
- Identify exoplanet science areas and key questions that will likely remain after these current and planned missions are completed.

- Identify key observational, technological, theoretical, and computational challenges for making progress in further understanding exoplanets and exoplanetary systems.
- Identify the opportunities and obstacles that need to be overcome to make medium-to-long-term progress in key observational, technological, and theoretical areas. Identify the resources that are required to make progress in these areas, and the time scale on which this progress is likely to be made.
- Discuss how to develop and expand partnerships (interagency, international, and public/private) in furthering understanding of the nature, formation, and evolution of exoplanets and exoplanetary systems.
- Identify likely fruitful cross-disciplinary topics and initiatives that will enable and accelerate progress in these future areas of exoplanet inquiry, including but not limited to: protoplanetary and debris disk science, stellar astrophysics, planetary science, and astrobiology.

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C

Exoplanet Detection Methods

This appendix describes in more physical and mathematical detail the primary methods of detecting planets. However, no attempt is made to be thorough or comprehensive. For more complete and detailed reviews, along with relevant references, see the book chapter "Exoplanet Detection Methods," by Wright and Gaudi (2013), and the textbooks *Exoplanets*, edited by S. Seager, and *The Exoplanet Handbook*, edited by M. Perryman.[1]

The remainder of this appendix adopts the following notation. The primary host has a mass M_*, radius R_*, density ρ_*, and luminosity L_*. The companion exoplanet has a mass M_p, radius R_p, density ρ_p, luminosity L_p, orbit with semimajor axis a, period P, and inclination i (where $\sin(i) = 1$ is edge-on). For noncircular orbits, depending on the detection technique, it may be possible to measure the eccentricity e, argument of periastron (which differ for the planet and host by π), the time of periastron, and longitude of the ascending node, but for simplicity this appendix will typically assume circular orbits.

RADIAL VELOCITY

The radial velocity (RV), or Doppler technique, is an indirect method that relies on measuring the Doppler shift of the star as it orbits the center-of-mass of the planet/star system. Since it is measuring the line-of-sight RV of the star, it is most sensitive to edge-on planetary systems. For a circular orbit, the general observables are the stellar velocity semiamplitude K and the period (as well as the time of periastron and the systemic velocity of the system). For a circular orbit the radial velocity curve as a function of time is a sinusoid; for eccentric orbits K depends on the eccentricity, and the precise shape of the curve reveals the eccentricity and argument of periastron.

The velocity semiamplitude is given by

$$K = \left(\frac{P}{2\pi G}\right)^{-1/3} \frac{M_p \sin i}{M_*^{2/3}} \left(1 - e^2\right)^{-1/2},$$

where it is assumed that $M_P \ll M_*$, $K \sim 13$ m/s, and $P \sim 12$ years for an edge-on Jupiter analogue orbiting a Sun-like star. For an edge-on Earth analogue orbiting a Sun-like star, $K \sim 10$ cm/s and $P \sim 1$ year. For a "hot Jupiter" with a period of ~3 days, $K \sim 150$ m/s. Therefore, to detect Jovian analogues generally requires RV accuracies of 1-10 m/s, Neptune-mass planets (~17 $M_\oplus$) on ~100 day orbits require ~1 m/s accuracies, and true Earth analogues require better than ~10 cm/s Doppler precision.

Generally, the intrinsic Doppler information content in the spectral lines of quiet late F, G, K, and M stars, if observed at sufficiently high resolution of $R \sim 60{,}000$ to resolve the lines, is sufficient to achieve precision of a few m/s for reasonable exposure times on currently existing 3-10 m telescopes. The

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[1] Dotson, R. 2010. *Exoplanets* (S. SEAGER, ed.). University of Arizona Press, Tucson; Perryman, M. 2011. *The Exoplanet Handbook*, Cambridge University Press, United Kingdom; and Wright J.T. and B.S. Gaudi. 2013. Exoplanet detection methods. Pp. 489-549 in *Planets, Stars and Stellar Systems* (T.D. Oswalt, L.M. French, and P. Kalas, eds.). Springer, Netherlands.

primary difficulty is therefore calibrating the wavelength of the spectral lines to the position on the detector to an accuracy that is much better than the precision. There have been two basic approaches to accomplish this. The first is to pass the starlight through a gas cell, whereby the lines of the gas in the cell (which have known rest wavelengths) are imprinted on the stellar spectra. The second is to build extremely stable spectrographs and use noncommon path calibration lamps. Both of these methods have been used to achieve Doppler precisions and accuracies of a few m/s.

Achieving precisions below this requires dealing with a host of additional systematics, which are described in detail in Chapter 4, in the section "Exoplanet Masses." Many of these can be dealt with by constructing ever more stable spectrographs and designing ever more precise and stable wavelength calibration methods, but it may well be that the ultimate limit in the accuracy of RV measurements is set by the intrinsic stellar variability, which causes what is colloquially referred to as "RV jitter."

The relatively weak function of K on P makes the RV method able to detect planets over a broad range of parameter space, although it is generally limited to detecting planets around slowly rotating stars (which largely eliminates main-sequence stars above the Kraft break of ~1.2 M_{sun} as good targets), and, at least to date, old, relatively inactive stars. Furthermore, unless the planet also transits or is directly detected, RV observations provide little detailed information about the detected planet itself. Other than the period and eccentricity of the orbit, RV observations alone only provide the minimum mass of the planet. A priori, the cosine of the inclination angle is uniformly distributed, implying that the true mass is typically close to the minimum mass. However, this statement assumes a uniform prior on the logarithm of the true mass, which may be a poor assumption for some regimes of the planet mass function.[2]

TRANSITS

In many ways, the transit technique is conceptually one of the simplest techniques to detect exoplanets, as it relies on the planet blocking a small amount of stellar light as the planet passes between the observer and the planet's host star. For exoplanets with nearly edge-on inclinations, or more specifically in the case of circular orbits when the impact parameter in units of the stellar radius satisfies the inequality

$$b \leqq \frac{a \cos i}{R_*}(1+k),$$

where $k = \frac{R_p}{R_*}$, the planet will pass in front of its parent star (transit) once per orbit, thereby blocking part of the light from the star. Assuming no limb darkening of the star and that the transit is complete—for example, $b < 1 - k$—then the fractional depth of the transit is simply k^2. Again for a circular orbit, the transit duration is

$$T \cong T_{eq}(1-b^2)^{1/2},$$

where the equatorial transit duration is

$$T_{eq} \equiv \frac{R_* P}{\pi a}.$$

Given that $\cos(i)$ is uniformly distributed for randomly oriented orbits, the a priori transit probability is $P_{tr} = \frac{R_*}{a}$, again assuming circular orbits and $R_P \ll R^*$. Note that the duty cycle of the

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[2] Ho S. and E.L. Turner. 2011. The posterior distribution of sin(i) values for exoplanets with M_T sin(i) determined from radial velocity data. *Astrophysical Journal* 739(1):26.

transit—that is, the fraction of the planet's orbit that it is passing in front of its parent star—is roughly $\frac{P_{tr}}{\pi}$ for an equatorial transit.

For a hot Jupiter orbiting a solar-type star, the transit probability is ~10 percent, the duty cycle is ~3 percent, the depth is of the transit ~1 percent, and it lasts for a few hours. For an Earth analogue, the transit probability is roughly $\frac{R_\odot}{AU} \sim 0.5$ percent, the depth is $\left(\frac{R_\oplus}{R_\odot}\right)^2$, or roughly 0.01 percent, and the duration is about 10 hours, corresponding to a duty cycle of only 0.15 percent.

The challenges of detecting hot Jupiters via transits are clearly very different from the challenges of detecting Earth analogues. In general, 1 percent relative photometry on bright stars can be achieved from the ground with relatively small-aperture telescopes. Indeed, smaller telescopes are preferred because they typically have larger fields-of-view for a fixed detector size. Therefore, essentially all of the hot Jupiters orbiting bright (V < 12) stars have been found by relatively small-aperture telescopes with diameters less than 20 cm and wide fields-of-view (many degrees), or arrays of such telescopes. On the other hand, it is generally exceptionally difficult to achieve relative photometric precisions of <0.1 percent from the ground, particularly simultaneously for a large number of stars.

Therefore, to detect true Earth analogues, space-based missions are required. Given the long periods, small duty cycles, and the low a priori transit probabilities, these missions need to not only achieve exquisite (10 micromagnitude) relative photometric precision, they need to do so for a large number (tens of thousands) of stars essentially continuously for several years. These requirements drove the design of NASA's Kepler space telescope, and similar considerations drove the requirements for NASA's recently launched Transiting Exoplanet Survey Satellite (although TESS will be sensitive to true Earth analogues over only a limited region of the sky), and is driving the design of the European Space Agency (ESA)'s Planetary Transits and Oscillations of Stars (PLATO).

The detection of transits of a planet alone yield only the period of the planet orbit and the radius of the planet (given a measurement of the radius of the star, which has fortunately now become routine for bright stars with Gaia). However, with sufficiently precise radial velocity follow-up, it is also possible to measure the density of the star and, when combined with R^* and M^*, to measure M_p, and R_p.[3] Thus, for transiting planets with radial velocity follow-up, it is possible to infer the density of the planet, which is the first step in determining its basic nature.

Finally, it is also possible to detect the existence of additional, nontransiting planets in transiting systems by searching for transiting timing variations. The detection of transit timing variations in multiple planet systems also enables the measurement of the masses of the planets without measuring the reflex radial velocity they induce on their parent star.

DIRECT IMAGING

Detecting exoplanets via direct imaging generally refers to resolving the light from an orbiting exoplanet from its parent star (rather than, e.g., the detection of the thermal emission of a transiting planet from eclipse spectroscopy). The challenges of direct imaging are generally the large flux ratio between the planet and the star, and the small angular separation between the planet and the much brighter host star.

The angular separation of a planet from its host star depends on all the Keplerian orbital elements, as well as on the epoch of observation and the distance to the system. For simplicity, one assumes a circular, face-on orbit, for which the angular separation is simply $\frac{a}{d}$, where d is the distance to the system.

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[3] Seager, S. and G. Mallen-Ornelas. 2003. A unique solution of planet and star parameters from an extrasolar planet transit light curve. *Astrophysical Journal* 585(2):1038.

For planets reflecting starlight, the planet/star flux ratio depends on the geometric albedo A_g, the phase and phase curve Φ of the planet, the radius of the planet, and the separation of the planet from the star,

$$f \cong A_g\,\Phi(\alpha)\left(\frac{R_p}{a}\right)^2.$$

For planets emitting in thermal emission, the flux ratio in the Rayleigh-Jeans tail (where the contrast is the largest) is

$$f \cong \left(R_p/R_*\right)^2\left(T_p/T_*\right).$$

For planets for which the thermal emission arises from reprocessed starlight, simple energy balance gives

$$\left(T_p/T_*\right) = (R_*/a)^{1/2}[f(1-A_B)]^{1/4},$$

where f accounts for the fraction of the planet surface over which the absorbed energy is reemitted, and A_B is the Bond (or total) albedo. In all the cases where planets have been directly imaged to date, however, the detections are of young (<300 Myr) giant (>2 M_J) planets whose luminosity and temperature are driven by released gravitational potential energy, and the planet's spectrum is significantly different from a black body, resulting in near-infrared planet to star flux ratios for young (<300 Myr) of 10^4 to 10^6. Although this flux ratio is large, it can be overcome with combinations of large ground-based telescopes, advanced adaptive optics (AO), sophisticated image processing, and coronagraphy. However, young stars are almost inevitably moderately distant from Earth and the necessary sensitivity is possible only beyond a few tenths of an arcsecond from the parent star; hence, almost all the imaged planets are giant (>2 M_J) planets orbiting at 20 AU or farther. As these planets are directly detected, it is also possible to obtain their spectra, which allows for inferences about their atmospheric composition. Also, these planets orbit far from young stars for which precision Doppler measurements are impossible, and therefore inferring their mass requires both an estimate of the age of the system and (generally poorly calibrated) evolutionary models. Astrometric measurements with Gaia should change this situation and in turn calibrate the models.

Directly detecting mature planets that are in equilibrium with their host stars via either reflected light or reprocessed thermal emission is generally much harder, and is expected to require space-based missions. This is simply due to the astonishingly small flux ratios between the planets and their host stars, and their small angular separation. Consider an Earth analogue orbiting a Sun-like star at a distance from Earth of 10 pc. The flux ratio of Earth to the star in reflected light (depending on albedo and phase) is roughly 10^{-10}, and the maximum angular separation is about 0.1 arcsecond (at quadrature)—that is, this requires detecting a 30th magnitude object located 0.1 arcsecond away from a 5th magnitude star. For a Jupiter analogue in the same system, the flux ratio is only $(10/5.2)^2 \sim 3.7$ times larger, since Jupiter is about 10 times larger than Earth but is roughly 5.2 times farther away. The fact that the separation is about 5 times larger at quadrature does relax the requirements for detecting Jupiter analogues in reflected light considerably. Directly detecting such a system generally requires not only going to space, but also requires sophisticated techniques to suppress the light from the star, as the wings of the Airy pattern of an unobstructed stellar point spread function are orders of magnitude larger than the brightness of the planet. Two promising techniques, which are described in detailed in the section "The Case for Imaging," in Chapter 4, are internal coronagraphs and external occulters (starshades). These techniques have been mathematically demonstrated to allow the detection of Earth and Jupiter analogues around the most nearby stars with telescopes as small as 4 m. However, they are nevertheless relatively immature technologies, and significant investment is needed to mature them to the point where they can confidently be flown on a future direct imaging mission.

Detecting mature planets in thermal emission is easier in terms of flux ratio than detecting them in reflected light, as the flux ratios are generally more favorable by about 10^4 orders of magnitude. However, for an Earth-like planet this emission peaks at approximately 10 microns. The diffraction limit of a 20 m telescope at 10 microns is 0.1 arcsecond. Constructing a diffraction-limited 20 m class space telescope that would be cold enough to operate at 10 microns is considered exceptionally difficult. Indeed, most credible paths toward achieving the resolution needed to detect Earth analogues in thermal emission is to employ a nulling interferometer, which uses smaller apertures separated by tens of meters, and provides a natural way to suppress the light from the primary star. Furthermore, interferometry is generally believed to be easier at longer wavelengths. Nevertheless, the former method (detecting the planets in reflected light) is currently generally believed to be the more straightforward path. That said, the common (although often unspoken) belief is that such a nulling, near-infrared (NIR) interferometry would be a necessary follow-up to any reflected light direct imaging mission, as detecting the exoplanet in thermal emission is not only required to measure the temperature of the planet but is also needed to measure its radius, and so (with an astrometric or radial velocity detection of the reflex motion of its host star and thus the mass of the planet) measure its density and thus determine if it is truly terrestrial.

The committee concludes this section by mentioning other avenues of directly detecting and studying potentially habitable, mature exoplanets from the ground using the next generation of ground-based large-aperture telescopes (GSMTs; for further discussion, see the section “Ground-Based Studies,” in Chapter 4). The next generation of ground-based telescopes (ELT, GMT, and TMT) will have apertures of 30 m to 40 m. At wavelengths of 1 micron, these telescopes will have a diffraction limit of about 0.005 arcsecond. Terrestrial planets orbiting in the habitable zones of nearby (few parsecs) M dwarfs will have maximum angular separations of their host star of several times larger than this. Furthermore, habitable planets orbiting M dwarfs have reflected-light flux ratios that are orders of magnitude larger than Earth analogues. It may also be possible to detect potentially habitable planets in thermal emission for several nearby systems. These systems can be discovered either by transit surveys (which are sensitive only to edge-on, and therefore generally more distant, systems) or radial velocity surveys. As discussed in the section “Ground-Based Studies,” it may also be possible to detect and characterizing planets in the thermal infrared (3-13 microns) using GSMTs.

MICROLENSING

Microlensing is an indirect method of detecting exoplanets that is primarily useful for the statistical characterization of the demographics of exoplanets over a broad range of host star and exoplanet parameter space. As described below, it is not optimal for characterizing individual exoplanets or exoplanetary systems.

The basics of the microlensing method are quite simple. It relies on the fact that gravity bends light, by an amount that can be quantitatively derived (to within a factor of 2) with Newtonian dynamics (the additional factor of 2 requires general relativity). Consider a star at a distance d_s (in this case, the star is typically in the galactic bulge). If another star, in the foreground galactic disk or galactic bulge, at a distance d_l, passes within roughly one milliarcsecond of the background star, it will split the light from that background star into two images, with separation of order the Einstein ring radius θ_{E}

$$\theta_{\mathrm{E}} = \left(\frac{4GM_*}{d_{\mathrm{rel}}c^2}\right)^{1/2}.$$

where $d_{rel}=d_l^{-1}-d_s^{-1}$ is proportional to the relative lens-source parallax. For typical parameters θ_{E}=1 mas, and thus two images are unresolved. However, the background stars are also magnified, by an amount that ranges of from a few millimagnitudes to factors of thousands. The closer the alignment of the lens and source, the larger the magnification. The images pass by the lens at a distance of order of the Einstein ring radius, and is thus

$$r_E = \theta_{\mathrm{E}} d_l,$$

which is typically a few AU to 5 AU for host stars with masses of roughly the mass of a typical M dwarf to a solar-mass star. The durations of the primary microlensing events are $t_E = \frac{\theta_{\mathrm{E}}}{\mu_{rel}}$, where μ_{rel} is the relative proper motion between the lens and source, which is typically 5-10 milliarcseconds per year, and thus the typical durations of microlensing events due to stars are a few days to hundreds of days.

In order to detect a planet with microlensing, the projected planet separation of the microlensing event needs to coincide with the location of the images. Thereby, the gravitational field of the planet further perturbs the images, revealing the existence of the planet. This leads to detection probabilities (given the presence of a planet) of about 1 percent for an Earth-mass planet up to 20 percent for a Jupiter-mass planet. Fortunately, the signals induced from these planets are typically large and unambiguous, unless the angular Einstein ring radius of the planet is substantially smaller than that of the angular size of the source, which generally occurs only for planets less massive than Earth.

Because of the low probability of detecting a stellar-mass microlensing event, and the lower probability of detecting the planetary perturbation even in the case that the microlensing event is detected and assuming the planetary companion exists, microlensing surveys for exoplanets generally require continuously monitoring hundreds of millions of stars on daily time scales to detect the microlensing events, and then monitoring the known microlensing events on hourly to daily time scales to detect the planetary perturbations. Recently, large-format (several square degree) detectors have been available, such that these goals can be simultaneously achieved with the same observatory setup, although round-the-clock (and thus several longitudinally distributed) telescopes are required.

As explained in the section “Expanding the Statistical Census of Exoplanets,” in Chapter 4, realizing the true potential of microlensing ultimately requires a space-based mission. Such a mission essential in that it would enable the competition of the statistical census of exoplanets begun by Kepler.

Planets detected via microlensing routinely measure the mass-ratio between the planet and the star, and the instantaneous projected separation between the planet and host star in units of the Einstein ring radius. Fortunately, there are many methods of breaking these degeneracies, and the microlensing survey with Wide-Field Infrared Survey Telescope (WFIRST) will enable the routine measurement of the host star and planet mass.

PULSAR TIMING

Pulsar timing relies on the exquisite timing that can be achieved by monitoring pulsars to search for deviations from nonuniform period. As described in Chapter 2, timing of the pulsar PSR 1257+12 by Wolszczan and Frail led to the discovery of the first pulsar planetary system, as well as the lowest-mass exoplanet yet discovered. Unfortunately, it turns out that pulsar planetary systems are quite rare, and thus do not provide significant insight into the formation of planetary systems.

ASTROMETRY

Astrometry, in some sense, provides the “ideal” method of detecting planetary systems, in that is sensitive to planets regardless of their inclination. Conversely, astrometry has many hindrances. First, the astrometric signals of planetary systems are incredibly small. For an Earth analogue at distance of 10 pc, the astrometric signal is

$$\alpha = \left(\frac{M_p}{M_*}\right)\left(\frac{a}{d}\right) = 0.3\mu as \left(\frac{M_p}{M_\oplus}\right)\left(\frac{M_*}{M_\odot}\right)^{-1}\left(\frac{a}{AU}\right)\left(\frac{d}{pc}\right)^{-1}.$$

This is well below any realistic astrometric accuracy achievable from the ground. Furthermore, the astrometric detection of a planet with period P is very difficult unless the survey has a duration of at least P. Combined with the fact that astrometric surveys are inherently the most sensitive to planets with periods at the limit of the survey implies that generally only the most massive planets with periods slightly less than the survey duration can be found in astrometric surveys.

An excellent example of this reality is the Gaia mission. While Gaia will have the most exquisite astrometric accuracy to date (<10 microarcseconds for V < 12), it will not open up a new region of exoplanet parameter space, as it will be sensitive only to planets with mass several times the mass of Jupiter at separations of several AU. While it will detect such planets in unprecedented numbers, it will not reveal new knowledge about the demographics of exoplanets. That said, Gaia will measure the true mass of the planets it detects (not just the minimum mass measured by radial velocity), it will provide knowledge of the coplanarity of exoplanet systems, and it will discover extremely rare (and valuable) planetary system "oddballs."

DISK PERTURBATIONS

In principle, planets too small to be directly observed in other ways could be inferred from their perturbations on their disks. Young planets perturb both gas and dust, including opening gaps and driving spiral arms; old planets can pile dust into resonances. Ground truth for the former is seen in the detection of planets around LkCa 15 and PDS 70 inside gaps.[4] Ground truth for the latter exists in the planet around Beta Pictoris, which was first predicted from the inclined inner disk and then discovered with direct imaging.[5]

OTHER METHODS

A variety of other methods have been proposed to detect exoplanets. One prominent example includes the detection of their radio emission. Unfortunately, despite their promise, to date none of these methods have led to the definitive detection of an exoplanet. Nevertheless, the committee concludes that these methods hold promise, and should continue to be explored.

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[4] See Sallum, S., K.B. Follette, J.A. Eisner, L.M. Close, P. Hinz, K. Kratter, J. Males, et al. 2018. Discovery of a planetary-mass companion within the gap of the transition disk around PDS 70. *Astronomy and Astrophysics*, in press.

[5] See Augereau, J.C., R.P. Nelson, A.M. Lagrange, J.C.B. Papaloizou, and D. Mouillet. 2001. *Astronomy and Astrophysics* 370:447.

D

Biosignature Table

TABLE D.1 Biosignature Table: Spectral Features as a Function of Wavelength Range That Could Be Sought for Identification of an Oxygenic Photosynthetic Biosphere

Molecules/ Feature	0.1-1.8 μm	1.8-2.5 μm	2.5-5.0 μm	5.0-20 μm	Notes
O_2	0.14, 0.2, 0.69, 0.76, 1.27			—	Biosignature sought—also disequilibrium pair with CH_4, N_2O.
O_3	0.2-0.3 (strong), 0.38-0.65		4.75	9.6	Biosignature sought—also disequilibrium pair with CH_4, N_2O.
O_4 (O_2-O_2 CIA)[a]	0.45, 0.48, 0.53, 0.57, 0.63, 1.06,1.27 (strong)			—	False positive indicator—dense O_2 from ocean runaway.[b]
CH_4	0.1-0.14, 0.79, 0.89, 1.0, 1.1, 1.4, 1.7	2.31 (strong)	3.3 (strong)	7.7	Biosignature sought—disequilibrium pair with O_2. Indicates presence of O_2 sink.[c] May be disequilibrium pair with CO_2.[d]
CO_2	0.14, 1.05, 1.21, 1.32, 1.44, 1.6	2.01, 2.75	4.3 (strong)	9.4, 10.4, 15	False positive indicator, especially in combination with CO—ongoing CO_2 photolysis.[e]
CO	1.6	2.35	4.65		False positive indicator, especially in combination with CO_2—ongoing CO_2 photolysis.[e]
N_4 (N_2-N_2 CIA)[f]			4.1		False positive discriminant—helps quantify noncondensible gas fraction, disequilibrium biosignature when paired with N_2/O_2.[g]
N_2O	0.13, 0.145, 0.185	2.11, 2.25	2.6, 2.67, 2.97, 3.6, 3.9, 4.3, 4.5	7.9, 17.0	Biosignature sought—disequilibrium pair with O_2.
H_2	0.64-0.66, 0.8-0.85				Possible bulk atmospheric constituent.
H_2O	0.13, 0.17, 0.65, 0.72, 0.82, 0.94, 1.12, 1.4	1.85	2.7	6.3	Habitability indicator. False positive discriminant—could show ocean loss or presence of catalyst for CO_2 recombination.[h]

Molecules/ Feature	0.1-1.8 μm	1.8-2.5 μm	2.5-5.0 μm	5.0-20 μm	Notes
SO_2	0.2, 0.29, 0.37		4.0	7.3, 8.8, 19.0	Desiccation marker. High amounts are likely incompatible with a surface ocean.[i]
Ocean glint[j]	0.8-0.9 (optimal)				Habitability indicator. False positive discriminant—disequilibrium biosignature when paired with O_2/N_2.[k]
Vegetation red edge	0.6 (halophile),[l] 0.7 (photosynthesis—G dwarf)[m]				Biosignature sought. Other pigments may also generate spectral edges.[n]
Seasonal variability	CO_2 (1.6), CH_4 (1.1 and 1.4), O_2/O_3			CO_2 (15)	Biosignature sought—seasonal variability in biomass building and metabolic output.[o]

NOTE: All values in the table are given in microns (μm) and molecular band wavelengths are derived from HITRAN; Rothman et al. (2013).[p] SOURCE: Table modified from Meadows (2017).[q]

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E

Committee and Staff Biographical Information

DAVID CHARBONNEAU, *Co-Chair*, is a professor of astronomy and a Harvard College Professor at Harvard University. His research focuses on the detection and characterization of exoplanets, with the goal of studying inhabited worlds, the development of novel observational methods in support of these efforts, and stellar astrophysics focusing on nearby solar and low-mass stars as planet hosts. Dr. Charbonneau led the team that made the first detection of transits of an exoplanet across its parent star; the first detection of an exoplanet atmosphere; and the first direct detection of light emitted by a planet outside the Solar System. Using data from the NASA Kepler mission, Dr. Charbonneau and his student Courtney Dressing determined the galactic frequency of occurrence of planets that were similar to Earth in both size and temperature. He currently leads the MEarth project, which has found several of the terrestrial exoplanets whose atmospheres are amenable to study with upcoming observatories, and he is a co-investigator on the NASA Transiting Exoplanet Survey Satellite (TESS) mission. Dr. Charbonneau has received numerous awards for his research, including the Alfred P. Sloan Research Fellowship, the David and Lucile Packard Fellowship for Science and Engineering, the Alan T. Waterman Award from the National Science Foundation (NSF), and the Medal for Exceptional Scientific Achievement from NASA, and he was the 2016 Blavatnik National Laureate in Physical Sciences and Engineering. He earned his Ph.D. in astronomy from Harvard University in 2001, and his B.Sc. in math, physics, and astronomy from the University of Toronto. In 2017 Dr. Charbonneau was elected to the National Academy of Sciences, and he previously served on the Astro2010 Panel on Planetary Systems and Star Formation.

B. SCOTT GAUDI, *Co-Chair*, is the Thomas Jefferson Professor for Discovery and Space Exploration and professor of astronomy at the Ohio State University Department of Astronomy. A member of the faculty since 2006, Dr. Gaudi is a leader in the discovery and statistical characterization of extrasolar planets using a variety of methods, including transits and gravitational microlensing. In 2008 he and his collaborators announced the discovery of the first Jupiter/Saturn analogue. Dr. Gaudi is deeply immersed in analytic and numerical techniques for assessing the yield, biases, and discovery potential of current and next-generation surveys to determine the demographics of exoplanets. Dr. Gaudi is a member of the Formulation Science Working Group for NASA's Wide-Field Infrared Survey Telescope (WFIRST) and is co-community chair of NASA's Habitable Exoplanet Observatory study. Dr. Gaudi was the 2009 recipient of the Helen B. Warner Prize of the American Astronomical Society (AAS), won a National Science Foundation (NSF) CAREER Award and Presidential Early Career Award in Science and Engineering (PECASE) in 2012, and received NASA's Outstanding Public Leadership Medal in 2017. Dr. Gaudi earned his Ph.D. in astronomy from Ohio State University.

FABIENNE A. BASTIEN is an assistant professor of astronomy and astrophysics in the Department of Astronomy and Astrophysics at the Pennsylvania State University (PSU). At PSU Dr. Bastien is leading efforts to understand the stellar processes that impact exoplanet detection and characterization and to find ways to mitigate or remove them. Her research interests include stellar variability, stellar astrophysics, exoplanet detection and characterization, the influence of stellar variations on exoplanet habitability, and stellar and planetary system evolution. Dr. Bastien was previously a NASA Hubble postdoctoral fellow at PSU. She earned her Ph.D. in physics from Vanderbilt University.

JACOB BEAN is an associate professor of astronomy and astrophysics at the University of Chicago. His research is focused on the use of ground- and space-based facilities to detect and characterize planets around nearby stars, with particular interest in studying planets around low-mass stars and in probing the atmospheres of the smallest known exoplanets. Dr. Bean previously served as a Sagan Fellow at Harvard University and a Marie Curie International Fellow at the University of Göttingen. He earned his Ph.D. in astronomy from the University of Texas at Austin.

JUSTIN R. CREPP is an associate professor of physics and the director of the Engineering and Design Core Facility at the University of Notre Dame. He designs and builds instruments for the largest telescopes in the world. Professor Crepp's research involves developing new technologies and observational techniques to detect and study planets orbiting other stars. Prior to working at Notre Dame, he was a postdoctoral scholar at the California Institute of Technology. He has published over 100 peer-reviewed journal articles. Professor Crepp was awarded a NASA Early Career Fellowship in 2013 for his work in studying brown dwarfs and extrasolar planets through direct imaging. Additionally, he won the National Science Foundation (NSF) CAREER Award in 2017 for his work to develop a new type of astronomical spectrograph that uses adaptive optics. He received his Ph.D. in astrophysics from the University of Florida.

ELIZA KEMPTON is an assistant professor of astronomy at the University of Maryland. Her research is focused on the detection and classification of exoplanets, with particular interest in the structure and observable properties of super-Earths and their atmospheres. Dr. Kempton previously served as a Sagan Fellow at the University of California, Santa Cruz. She has received numerous awards, including the Cottrell Scholar Award from the Research Corporation for Science Advancement and the National Science Foundation (NSF) CAREER Award. Dr. Kempton earned her Ph.D. in astronomy at Harvard University.

CHRYSSA KOUVELIOTOU is a professor of astrophysics at The George Washington University (GWU) and the director of GWU/Astronomy, Physics, and Statistics Institute of Sciences. Before joining GWU, Dr. Kouveliotou was at NASA Marshall Space Flight Center (MSFC) in Huntsville, Alabama, from which she retired as a senior technologist of high-energy astrophysics. Her research interests include high-energy astrophysical transients, in particular, gamma ray bursts (GRBs) and magnetars, which she discovered in 1998; she has also published papers on X-ray binaries, solar flares, and merging galaxy clusters. Dr. Kouveliotou has initiated large research projects and collaborations in the United States and Europe. She is an affiliate scientist of the NASA/Swift and Fermi missions. She has 454 refereed publications, with a Hirsh-index of 90 and 37,699 citations (ADS; refereed and nonrefereed publications). In 2013, Dr. Kouveliotou chaired the team of the 30-Year Roadmap of NASA's Science Mission Directorate (SMD)/Astrophysics Division. Dr. Kouveliotou has received multiple awards, including the Descartes Prize, the Rossi and Heineman Prize, and the NASA Exceptional Service Medal and Space Act Award. She has been decorated by the Greek Government as a Commander of the Order of the Honor, for excellence in science. Dr. Kouveliotou has a Ph.D. in astrophysics from the Technical University of Munich, an M.Sc. in astronomy from the University of Sussex, and two honorary degrees, from the Universities of Sussex (UK) and Amsterdam. In addition to the National Academy of Sciences (NAS), she is a member of the U.S. Academy of Arts and Sciences and a foreign/corresponding member of the Dutch Royal Academy and the Greek National Academy. Dr. Kouveliotou has been a councilor and a vice president of the American Astronomical Society (AAS) and a president of the HEAD (AAS) and DAP (American Physical Society), and she is the president of Division D of the International Astronomical Union. She is currently a member of the Executive Council of the NAS Space Studies

Board and the Committee on Council Affairs of the American Association for the Advancement of Science.

BRUCE A. MACINTOSH is a professor of physics at Stanford University. His research focuses on the detection of extrasolar planets (primarily through direct imaging) and on using adaptive optics to shape the wavefronts of light for a variety of applications. Dr. Macintosh is a co-discoverer of four planets orbiting the star HR 8799 and is the principal investigator (PI) of the Gemini Planet Imager, an advance adaptive optics planet-finder for the Gemini South Telescope. He also leads one of the science investigation teams for the Coronagraph Instrument for the Wide-Field Infrared Survey Telescope (WFIRST) mission. Dr. Macintosh served on the Exoplanet Task Force in 2006. He received his Ph.D. in astrophysics at University of California, Los Angeles. Dr. Macintosh has served as a member on the National Academies Astro2010 Panel on Optical and Infrared Astronomy from the Ground, the Committee on the Review of Progress Toward the Decadal Survey Vision in New Worlds, New Horizons in Astronomy and Astrophysics. He is currently a member of the Committee on Astronomy and Astrophysics.

DIMITRI P. MAWET is an associate professor of astronomy at the California Institute of Technology. He is also a senior research scientist at the Jet Propulsion Laboratory (JPL), and his research is focused on the formation and evolution of extrasolar planetary systems, as well as optical and infrared astronomy instrumentation. Dr. Mawet previously served as research scientist at JPL and operations staff astronomer and instrument scientist for the Very Large Telescope (VLT) of the European Southern Observatory (ESO). Dr. Mawet invented the Vector Vortex Coronagraph, an instrument to image exoplanets, and has (co-) authored more than 300 scientific publications. He has received multiple awards, including the ESO Exceptional Performance Award, the NASA Group Achievement Award, and the JPL Team Award for outstanding contributions to the Exoplanet Coronagraph Technology Group. Dr. Mawet was a Marie Curie Fellow at the Paris-Meudon Observatory (France) in 2002 and at the Institut of Astrophysique Spatiale in Orsay (France) in 2003. He received postdoctoral training as a NASA postdoctoral fellow at the Jet Propulsion Laboratory. He received his Ph.D. in sciences from the University of Liège.

VICTORIA S. MEADOWS is a professor of astronomy at the University of Washington in the Department of Astronomy. There, she is also director of the Astrobiology Program and principal investigator for the NASA Astrobiology Institute’s Virtual Planetary Laboratory. Dr. Meadows’s research interests include theoretical modeling of terrestrial planetary environments to understand their habitability, the generation and detectability of planetary biosignatures and their false positives, and Solar System planetary observations. The overarching goal of her research is to determine how to recognize whether a distant extrasolar planet can or does support life. Previously, Dr. Meadows was a research scientist at the Jet Propulsion Laboratory (JPL) and an associate research scientist at the Spitzer Science Center at the California Institute of Technology. She is a recipient of several NASA Group Achievement Awards, has been on the SETI Institute Science Advisory Board, and was a Frontiers of Science Kavli Fellow. She earned her Ph.D. in physics from the University of Sydney. Dr. Meadows served on the National Academies Searching for Life Across Space and Time: A Workshop committee and is currently a member of the Committee on Astrobiology Science Strategy for the Search for Life in the Universe.

RUTH MURRAY-CLAY is an associate professor of astronomy and astrophysics and associate department chair in the Department of Astronomy and Astrophysics at the University of California, Santa Cruz (UCSC), where she holds the E.K. Gunderson Family Chair in Theoretical Astrophysics. Dr. Murray-Clay’s research explores physical processes that shape the structure and evolution of planetary systems from a broad theoretical perspective. Her work emphasizes developing observational tests of theoretical ideas, with the goal of explaining and organizing the diversity of observed planetary system architectures. She has particular interests in planet formation, gravitational dynamics of extrasolar planets and Solar System bodies, the structure of protoplanetary disks, and mass loss from planetary atmospheres.

Previously, Dr. Murray-Clay was a faculty member in the Department of Physics at the University of California, Santa Barbara, a federal astrophysicist at the Smithsonian Astrophysical Observatory, and an affiliate of the Harvard University Department of Astronomy. She is a recipient of the Helen B. Warner Prize from the American Astronomical Society, the Ron Ruby Award for Teaching Excellence in the Physical and Biological Sciences at UCSC, and a National Science Foundation (NSF) CAREER award. Dr. Murray-Clay is also a Kavli Fellow of the National Academy of Sciences. She earned her Ph.D. in astrophysics from the University of California, Berkeley.

EVGENYA L. SHKOLNIK is an assistant professor of astrophysics at Arizona State University in the School of Earth and Space Exploration. She is an expert on exoplanets and stars, including the Sun, and studies stellar activity and star-planet interactions using ground and space telescopes to answer questions involving stellar evolution, exoplanet magnetic fields, and planet habitability. She is the principal investigator (PI) of the NASA Star-Planet Activity Research CubeSat (SPARCS) mission, and PI of the Hubble Space Telescope (HST)'s Habitable Zones and M Dwarf Activity Across Time (HAZMAT) program. Dr. Shkolnik is also a member of the NASA Astrobiology Institute Virtual Planetary Laboratory, and is on several science and technology advisory committees for upcoming space missions. Dr. Shkolnik previously was an astronomer at Lowell Observatory, a Carnegie Postdoctoral Fellow in the Department of Terrestrial Magnetism at the Carnegie Institution for Science, and a National Research Council Postdoctoral Fellow at the University of Hawaii in Manoa. She earned her Ph.D. in astrophysics from the University of British Columbia. Asteroid Shkolnik (25156) was named for her.

IGNAS SNELLEN is a professor of observational astrophysics at Leiden University in the Netherlands. Dr. Snellen's research is focused on the development of new techniques and ground-based instrumentation for the detection and characterization of extrasolar planets. He previously served as an astronomy lecturer at the University of Edinburgh. Dr. Snellen received his Ph.D. in astrophysics from Leiden University.

ALYCIA J. WEINBERGER is a staff scientist at the Carnegie Institution of Washington in the Department of Terrestrial Magnetism. Dr. Weinberger's research is focused on observational astrophysics, planet formation and circumstellar disks, young stars, exoplanets, and high angular resolution imaging. She is currently a member of the NASA Large Binocular Telescope Interferometer Key Science Team, the SOFIA Science Council, and the Magellan Telescope Science Advisory Committee. Previously, Dr. Weinberger served as a NICMOS Postdoctoral Research Astronomer and Astrobiology Postdoctoral Fellow at UCLA. She has received multiple awards and fellowships, including the Annie Jump Cannon Award in Astronomy from the American Association of University Women and the American Astronomical Society (AAS), as well as the Vainu Bappu Gold Medal from the Astronomical Society of India. Dr. Weinberger earned her Ph.D. in physics from the California Institute of Technology.

STAFF

DAVID B. LANG*, Study Director* (until May 2018)*,* is a former senior program officer for the National Academies Board on Physics and Astronomy (BPA) and joined the National Academies in 2004. Mr. Lang received a B.S. in astronomy and astrophysics from University of Michigan and a master's degree in engineering and public policy from University of Maryland. At the BPA, he has operated many large committees on scientific and technical policy issues including spectrum management and telecommunications, astronomy and astrophysics, plasma science, particle physics, plasma physics, and materials science. Mr. Lang also works with the board to identify pressing policy issues through discussions with policy makers and the science community.

NATHAN J. BOLL, *Study Director* (after May 2018), is an associate program officer with the Space Studies Board (SSB) and the Aeronautics and Space Engineering Board (ASEB) of the National Academies of Sciences, Engineering, and Medicine. He previously served as a research assistant in civil and commercial space at the Congressional Research Service in the Library of Congress and as a Christine Mirzayan Science and Technology Policy Graduate Fellow at the National Academies. Mr. Boll's background in space policy and science communication includes experience in the Office of International and Interagency Relations at NASA Headquarters, in the Aeronautics and Space Academies at the NASA Glenn Research Center, and as a member of the advisory board of the Montana Space Grant Consortium. Nathan earned his M.S. in space sciences from the University of Michigan, his M.A. in international science and technology policy from George Washington University, and his B.S. in mathematics from the University of Montana Western.

ARTHUR A. CHARO has been a senior program officer with the Space Studies Board (SSB) since 1995. For most of this time, he has worked with the board's Committee on Earth Science and Applications from Space and the Committee on Solar and Space Physics. Dr. Charo has directed studies resulting in some 37 reports, notably inaugural National Research Council (NRC) decadal surveys in solar and space physics (2002) and Earth science and applications from space (2007). He also served as the study director for the second NRC decadal survey in solar and space physics (2012) and was recently the study director for the second Earth science decadal, which was release at the end of 2017. Dr. Charo received his Ph.D. in experimental atomic and molecular physics in 1981 from Duke University and was a post-doctoral fellow in chemical physics at Harvard University from 1982-1985. He then pursued his interests in national security and arms control as a fellow, from 1985-1988, at Harvard University's Center for Science and International Affairs. From 1988-1995 Dr. Charo worked as a senior analyst and study director in the International Security and Space Program in the Congressional Office of Technology Assessment. In addition to contributing to SSB reports, he is the author of research papers in the field of molecular spectroscopy, reports on arms control and space policy, and the monograph *Continental Air Defense: A Neglected Dimension of Strategic Defense* (University Press of America, 1990). Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and a Harvard-Sloan Foundation Fellowship (1987-1988). He was a 1988-1989 American Association for the Advancement of Science (AAAS) Congressional Science Fellow, sponsored by the American Institute of Physics.

CHRISTOPHER J. JONES is a program officer for the Computer Science and Telecommunications Board. He joined the National Academies earlier in 2016 as a Mirzayan Science and Technology Policy Fellow for the Board on Science, Technology, and Economic Policy. Prior to this, Dr. Jones was a start-up founder working in the connected car and energy efficiency domain, a White House Fellow working on material science and water issues, and a Fulbright grantee assessing arsenic removal technologies for contaminated drinking water. Dr. Jones received his Ph.D. and M.A. from Rice University and B.S. from Florida State University, all in chemistry.

DIONNA WISE is a program coordinator with the Space Studies Board (SSB); she previously worked for the National Academies Division of Behavioral and Social Sciences and Education for 5 years. Ms. Wise has a long career in office administration, having worked as a supervisor in a number of capacities and fields. Ms. Wise attended the University of Colorado, Colorado Springs, and majored in psychology.

LAURA J. CUMMINGS is a Lloyd V. Berkner Space Policy Intern with the National Academies of Sciences, Engineering, and Medicine. Ms. Cummings is primarily interested in the interplay between international relations and the burgeoning field of space law. As an undergraduate she researched the possibility of international collaboration facilitating the construction of a global sunshade. Ms. Cummings graduated magna cum laude in general honors from the University of Colorado with B.A.'s in international affairs and astronomy. She will be pursuing a joint M.A. in international relations and J.D. at the University of Denver.

MICHAEL H. MOLONEY was the director of the Space Studies Board (SSB) and the Aeronautics and Space Engineering Board (ASEB) of the National Academies, through April 2018. Since joining the ASEB and SSB Dr. Moloney has overseen the production of more than 60 reports, including five decadal surveys, in astronomy and astrophysics, Earth science and applications from space, planetary science, microgravity sciences, and solar and space physics. He has also been involved in the review of NASA's space technology roadmaps and oversaw a major report on the rationale for and future direction of the U.S. human spaceflight program, as well as reports on issues such as NASA's strategic direction, lessons learned from the decadal survey processes, the science promise of CubeSats, the challenge of orbital debris, the future of NASA's astronaut corps, NASA's aeronautical flight research program, and national research agendas for autonomy and low-carbon propulsion in civil aviation. Since joining the National Academies in 2001, Dr. Moloney has also served as a study director at the National Materials Advisory Board, the Board on Physics and Astronomy (BPA), the Board on Manufacturing and Engineering Design, and the Center for Economic, Governance, and International Studies. Dr. Moloney has served as study director or senior staff for a series of reports on subject matters as varied as quantum physics, nanotechnology, cosmology, the operation of the nation's helium reserve, new anti-counterfeiting technologies for currency, corrosion science, and nuclear fusion. Before joining the SSB and ASEB in 2010, Dr. Moloney was associate director of the BPA and study director for the 2010 decadal survey for astronomy and astrophysics (*New Worlds, New Horizons in Astronomy and Astrophysics*). In addition to his professional experience at the National Academies, Dr. Moloney has more than 7 years' experience as a Foreign Service officer for the Irish government—including serving at Ireland's embassy in Washington and its mission to the United Nations in New York. A physicist, Dr. Moloney did his Ph.D. work at Trinity College Dublin in Ireland. He received his undergraduate degree in experimental physics at University College Dublin, where he was awarded the Nevin Medal for Physics. Dr. Moloney is a corresponding member of the International Academy of Astronautics and a Senior Member of the American Institute of Aeronautics and Astronautics. He is also a recipient of a distinguished service award from the National Academies of Sciences, Engineering, and Medicine.

RICHARD ROWBERG was the acting director of the Aeronautics and Space Engineering Board (ASEB) and the Space Studies Board (SSB) of the National Academies of Sciences, Engineering, and Medicine, between April 2018 and July 2018. Dr. Rowberg is currently on phased retirement and is a senior advisor for the Division on Engineering and Physical Sciences (DEPS) of the National Academy of Sciences (NAS). Prior to his retirement from NAS, Dr. Rowberg was deputy executive director of DEPS. He has served at NAS since 2002. From 1985 to 2001 he worked for the Congressional Research Service of the Library of Congress. From 1994 to 2001 Dr. Rowberg was a senior specialist in science and technology with the Resources, Science, and Industry Division, and from 1985 to 1994 he was chief of the Science Policy Research Division. From 1975 to 1985 Dr. Rowberg worked for the Congressional Office of Technology Assessment (OTA). From 1975 to 1979 he served as an analyst in and deputy manager of the OTA Energy Program, and from 1979 to 1985 he was manager of the OTA Energy and Materials Program. From 1969 to 1974 Dr. Rowberg was a research engineer and adjunct assistant professor in the Department of Electrical Engineering of the University of Texas, Austin. He received a B.A. in physics from UCLA in 1961, and a Ph.D. in plasma physics from UCLA in 1968. In 2010 Dr. Rowberg was elected a fellow of the American Physical Society.

COLLEEN HARTMAN is the Director of the Aeronautics and Space Engineering Board (ASEB) and the Space Studies Board (SSB) of the U.S. National Academies of Sciences, Engineering, and Medicine. Dr. Hartman has served in various senior positions, including Acting Associate Administrator, Deputy Director of Technology and Director of Solar System Exploration at NASA's Science Mission Directorate and Deputy Assistant Administrator at the National Oceanic and Atmospheric Administration. Dr. Hartman was instrumental in developing innovative approaches to powering space probes destined for the farthest reaches of the solar system, including in-space propulsion and nuclear power and propulsion.

She also gained administration and congressional approval for an entirely new class of competitively selected missions called "New Frontiers," to explore the planets, asteroids and comets in the Solar System. Dr. Hartman has built and launched balloon and spacecraft payloads, worked on robotic vision, and served as Program Manager for dozens of space missions, including the Cosmic Background Explorer (COBE). Data from the COBE spacecraft gained two NASA-sponsored scientists the 2006 Nobel Prize in Physics. Dr. Hartman earned a bachelor's degree in zoology from Pomona College in Claremont, Calif., a master's in public administration from the University of Southern California, and a doctorate in physics from the Catholic University of America. She started her career as a Presidential Management Intern under Ronald Reagan. Her numerous awards include the Claire Booth Luce Fellowship in Science and Engineering, the NASA Outstanding Performance Award, and multiple Presidential Rank Awards, one of the highest awards bestowed by the President of the United States to senior executives.

JAMES C. LANCASTER is the director of the Board on Physics and Astronomy (BPA) and acting director of the National Materials and Manufacturing Board. He joined the BPA as a program officer in 2008 and has been responsible staff officer for a number of studies, including the decadal survey on nuclear physics—*Nuclear Physics: Exploring the Heart of the Matter*, *An Assessment of the Science Proposed for the Deep Underground Science and Engineering Laboratory (DUSEL)*, *Research at the Intersection of the Physical and Life Sciences*, *Frontiers in Crystalline Matter: From Discovery to Technology*, and *Selling the Nation's Helium Reserve*. Prior to joining the BPA, Dr. Lancaster served on faculty at Rice University, where he taught introductory physics to science and engineering students, and as a staff researcher, where he participated in experimental investigations of the interactions of highly excited atoms with electromagnetic pulses and surfaces. In addition to his M.A. and Ph.D. degrees in physics from Rice University, Dr. Lancaster holds a B.A degree in economics from Rice University and a J.D. degree from the University of Texas School of Law. Prior to entering the field of physics, Dr. Lancaster practiced law for more than 12 years, specializing in the financial structuring and restructuring of businesses.

F

Acronyms

1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
AAS	American Astronomical Society
AGU	American Geophysical Union
ALMA	Atacama Large Millimeter/Submillimeter Array
APLC	apodized pupil Lyot coronagraph
AO	adaptive optics
ARIEL	Atmospheric Remote-Sensing Infrared Exoplanet Large-Survey
AU	astronomical unit
CARMENES	Calar Alto High-Resolution Search for M Dwarfs with Exoearths with Near-Infrared and Optical Échelle Spectrographs
CASE	Contribution to ARIEL Spectroscopy of Exoplanets
CCD	charge coupled device
CFAO	Center for Adaptive Optics
CHEOPS	Characterising Exoplanet Satellite
CoRoT	Convection, Rotation, and Planetary Transits
COS	Cosmic Origins Spectrograph
CUTE	Colorado Ultraviolet Transit Experiment
DOD	Department of Defense
DST	Decadal Survey Testbed
ELT	Extremely Large Telescope
EMCCD	electron multiplying charge coupled device
EOS	equations of state
EPRV	extremely precise radial velocity
ERS	European remote sensing satellite
ERS	Early Release Science
ESA	European Space Agency
ESPRESSO	Échelle Spectrograph for Rocky Exoplanet- and Stable Spectroscopic Observations
EUV	extreme ultraviolet
ExAO	extreme adaptive optics
ExEP	Exoplanet Exploration Program
Exo-C	Exoplanet Direct Imaging: Coronagraph
Exo-S	Exoplanet Direct Imaging: Starshade
ExoPAG	Exoplanet Exploration Program Analysis Group

FFP	free-floating planet
FGS	fine guidance sensor
FIES	Fiber-Fed Échelle Spectrograph
FIR	far infrared
FOV	field-of-view
FUV	far ultraviolet
GALEX	Galaxy Evolution Explorer
G-CLEF	Giant Magellan Telescope-Consortium Large Earth Finder
GCM	general circulation model
GMT	Giant Magellan Telescope
GMTNIRS	Giant Magellan Telescope Near-Infrared Spectrograph
GPI	Gemini Planet Imager
GSMT	giant segmented mirror telescope
Gyr	billion years
HabEx	Habitable Exoplanet Imaging Mission
HARPS	High Accuracy Radial Velocity Planet Searcher
HARPS-N	High Accuracy Radial Velocity Planet Searcher-North
HD	hydrogen deuteride
HDS	High Dispersion Spectroscopy
HIRIS	High Resolution Imaging Spectrometer
HITRAN	high-resolution transmission
HOSTS	Hunt for Observable Signatures of Terrestrial Systems
HROS	High-Resolution Optical Spectrometer
HST	Hubble Space Telescope
HZ	habitable zone
IFS	Integral Field Spectrograph
IFU	Integral Field Unit
IR	infrared
IR-APD	infrared avalanche photodiodes
IRDIS	Infra-Red Dual-Beam Imager and Spectrograph
IWA	inner working angle
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KELT-FUN	Kilodegree Extremely Little Telescope Follow-Up Network
KGMT-FUN	Korean Giant Magellan Telescope Follow-Up Network
KMTNet	Korean Microlensing Telescope Network
L2	Lagrange 2 point
LBT	Large Binocular Telescope
LBTI	Large Binocular Telescope Interferometer
LCOGT	Las Cumbres Observatory Global Telescope
LRS	Low Resolution Spectrometer
LSST	Large Synoptic Survey Telescope
LTE	local thermodynamic equilibrium
LUVOIR	Large UV/Optical/IR Surveyor

M_E	mass—Earth
M_J	mass—Jupiter
M_P	mass—planet
METIS	Mid-Infrared E-ELT Imager and Spectrograph
MHD	magnetohydrodynamics
MIR	mid-infrared
MIRI	Mid-Infrared Instrument
MKID	microwave kinetic inductance detector
MOA	Microlensing Observations in Astrophysics
MRI	magnetorotational instability
MRS	Medium Resolution Spectroscopy
MS	main sequence
Myr	million years

NAI	NASA Astrobiology Institute
NASA	National Aeronautics and Space Administration
NExSS	Nexus for Exoplanet Systems Science
ngVLA	Next Generation Very Large Array
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
NIR	near infrared
NIRES	Near-Infrared Échelle Spectrometer
NN-EXPLORE	NASA-NSF Exoplanet Observational Research
NOAO	National Optical Astronomy Observation
NSF	National Science Foundation
NUV	near ultraviolet

OGLE	Optical Gravitational Lensing Experiment
OST	Origins Space Telescope
OWA	Outer Working Angle

PI	principal investigator
PLATO	Planetary Transits and Oscillations of Stars
PM	phase modulation
PRIME	Prime focus Infrared Microlensing Experiment
PSF	point spread function

QE	quantum efficiency

R*	radius—star
R_e	radius—Earth
R_p	radius—planet
R&D	research and development
RMS	root-mean-square
RT	radiative transfer
RV	radial velocity

SAG	Study Analysis Group
SCDA	Segmented Coronagraph Design and Analysis
SDT	science definition team
SED	spectral energy distributions
SHW2018	Sexual Harassment of Women (National Academies 2018 report)

SIM	Space Interferometry Mission
SNR	signal-to-noise ratio
SPARCS	Star-Planet Activity Research CubeSat
SPECULOOS	Search for Habitable Planets Eclipsing Ultra-Cool Stars
SPHERE	Spectro-Polarimetric High-Contrast Exoplanet Research
SSB	Space Studies Board
STDT	Science and Technology Definition Team
STEM	science, technology, engineering, and mathematics
STIS	Space Telescope Imaging Spectrograph
STScI	Space Telescope Science Institute
TDEM	Technology Demonstration for Exoplanet Missions
TESS	Transiting Exoplanet Survey Satellite
TMT	Thirty Meter Telescope
TPF-C	Terrestrial Planet Finder Coronagraph
TPF-I	Terrestrial Planet Finder Interferometer
TRAPPIST	Transiting Planets and Planetesimals Small Telescope
TRL	technology readiness level
TTV	transit timing variation
URM	underrepresented minority group
vc	vortex coronagraph
Vis	visible
VLT	Very Large Telescope
VLTI	Very Large Telescope Interferometer
WISE	Wide-field Infrared Survey Explorer
WFIRST	Wide-Field Infrared Survey Telescope
WFIRST-CGI	Wide-Field Infrared Survey Telescope-Coronagraph Instrument
WIETR	WFIRST Independent External Technical/Management/Cost Review
XRP	Exoplanets Research Programs
XUV	extreme ultraviolet

G

Glossary

Ab initio: Latin term meaning “from the beginning.”

Abiotic: Of or relating to nonliving things; independent of life or living organisms.

Adaptive optics: A set of techniques to adjust the shape of mirrors on time scales of a fraction of a second to correct for rapid fluctuations in image quality. In the astronomical community, this term is used for systems that correct for distortions in images of ground-based telescopes due to atmospheric turbulence. The essential feature of the implementation is use of real-time sensing of the wave front from a distant source to provide the signals to the actuators that control the shape of the mirror.

Aerosol: A suspension of fine solid particles or liquid droplets in a gas.

Aerosol scattering: The scattering of light produced by small solid particles or liquids that are suspended in a gas.

Albedo: The fraction of light that is reflected from the surface of a planetary body.

Amorphous metals: Metals that have a noncrystalline atomic structure, and are instead arranged in a glass-like atomic structure. However, they are highly conductive.

Aperture: The diameter of the primary lens or mirror of a telescope; hence, the simplest single measure of the light-gathering power of a telescope.

Asteroseismology: The study of the interior structure of stars based on observed stellar oscillations.

Astrometry: The precise measurement of stellar positions. In exoplanet hunting, the astrometric method consists of making precise stellar location measurements, and searching for motion of a star around a common center of mass with a planet.

Biogenic: A substance produced by living organisms; produced or brought about by living organisms.

Biosignature: A global impact of life on its planetary environment that may be detectable at interstellar distances. Examples include atmospheric gases produced by life, characteristic surface reflectivity due to vegetation pigments or internal leaf structure, and seasonal changes in either of these due to life.

Bolometric: Measured over all wavelengths.

Chord: A “line,” or the path of an object, as it transits in front of another body.

Circumstellar disk: A broad ring of material orbiting around a star.

Coronagraph: A telescopic piece employed to block out the direct light from a star, to enable the viewing of nearby objects and coronal activity.

Debris disk: A disk created by ongoing collisions or evaporation of planetesimals that can exist for long times after the primordial disk (which was largely molecular hydrogen) has disappeared.

Diffraction limit: The finest detail that can be discerned with a telescope. The physical principle of diffraction limits this to a value proportional to the wavelength of the light observed divided by the diameter of the telescope.

Doppler shift: The change in frequency or wavelength of a wave, due to movement relative to the source. When movement is toward the observer, waves shift to shorter wavelength. When the movement is away from the observer, waves shift to longer wavelength.

Emission spectrum: A spectrum composed solely or predominantly of emission, including lines indicating the presence of a hot gas or thermal radiation as a result of a body's heat.

Ephemeris: The precise current, and sometimes future, positions of celestial objects.

eta-Earth ($\eta_\oplus$): The mean number per star of rocky planets with between 1 and 1.5-2 Earth-radii that reside in the habitable zone of their host star.

Exozodiacal dust: 1-100 micrometer grains of warm dust in extrasolar planetary systems; the analogue to zodiacal dust in the Solar System.

Fabry-Perot etalon: An interferometer that uses interference conditions of a wave reflected between two surfaces to maximize wavelength resolution.

Free-floating planet: A planetary-mass object that has been ejected from its home system, and orbits the galactic center directly, not gravitationally bound to any star or brown dwarf.

Habitable zone: The region around a star where a terrestrial planet with an Earth-like atmosphere could support surface liquid water. The habitable zone is calculated using stellar irradiation, orbital parameters and a 1D or 3D climate model. The inner edge occurs when an Earth-like planet experiences a runaway greenhouse. The outer edge calculation assumes that atmospheric CO_2 increases with orbital distance (and decreasing irradiation) until a maximum greenhouse limit is reached.

Inner working angle: For a coronagraph, the inner working angle is the smallest angular separation from the host star beyond which a planet of a given flux ratio can be imaged.

Insolation: The amount of stellar radiation reaching a given surface area; power per unit area.

Interferometer: An instrument that utilizes interference between beams of light to extract information about the source based upon the interference pattern generated.

Magneto-hydrodynamics: The branch of physics that studies the motion of electrically conductive fluids in electric and magnetic fields

Magnetorotational instability (MRI): A theory for how turbulence in an ionized gas subjected to an external magnetic field is generated. Turbulence is required to remove angular momentum from disk gas and allow accretion of the disk onto the star.

Metallicity: The sum total of elements within an object other than hydrogen and helium. Astronomers often lump these disparate elements together because they follow a common abundance trend in many astronomical objects. That is, an object that has low or high metallicity will have similarly low and high abundances of individual heavy elements like carbon, oxygen, silicon, and iron.

Microlensing: A technique used in the search for extrasolar planets that measures the changes in brightness of a background star as it is gravitationally lensed by a foreground star and its planet.

Occulter: An object or instrument that is used to block the light of an intended target.

Ohmic heating: Heating that occurs due to electric current flowing through a resistant medium.

Photochemical haze: A haze created from the interaction of atmosphere and stellar radiation (most commonly ultraviolet radiation).

Photochemistry: Chemical reactions cause by interaction with light. Most commonly this is used to describe interactions from the absorption of ultraviolet, visible, and infrared radiation.

Photoevaporation: The interaction of light with the molecules in a planet's atmosphere, which results in the loss of atmosphere. High-energy photons can accelerate or heat atmospheric molecules, enabling them to reach escape speed and be stripped from the atmosphere.

Photoionization: The process in which a photon interacts with an atom or molecule and energizes the atom to the point that it ejects an electron.

Photolyze: To break down molecules with light.

Photometry: The precise measurement of an object's electromagnetic radiation, usually summed over a small range of wavelengths at once.

Photosystem: The biochemical mechanism in planets in which chlorophyll absorbs light energy to use for photosynthesis.

Planetesimal: A rocky and/or icy body, of size from about 100 m to tens of kilometers, which was formed in the protoplanetary disk

Polarimetry: The measurement and interpretation of the polarization of waves. This is an exoplanet hunting technique as well. Light reflected by a planet is polarized due to a number of phenomenon, such as gaseous scattering, aerosol scatter, and reflection from the surface, and this light can be used as a direct-detection method for exoplanets.

Protoplanetary disk: A circumstellar disk of matter, including gas and dust, from which planets may eventually form or be in the process of forming

Reducing atmosphere: An atmospheric condition in which free oxygen or other oxidizing gases are limited, preventing oxidation.

Rovibrational transitions: Molecular transitions involving both vibrational and rotational states, used in rotational-vibrational spectroscopy.

Semimajor axis: One-half of the major axis (which runs through both foci) of an ellipse. For most planetary orbits, this is comparable to the separation between the planet and its star.

Serpentization: A metamorphic process in which ultrabasic rocks react with water to create a variety of hydrous, magnesium-iron phyllosilicate minerals known collectively as serpentine. The process is endothermic and results in the liberation of hydrogen, methane, and hydrogen sulfide.

Snow line: The region of a disk that separates where a volatile, such as water or CO, is in the gas or solid phase. This location depends on temperature and pressure and is thus a line that changes as a function of radial and vertical location in the disk as well as over time. Snow lines are thought to be important for changing the composition of solid material and for changing the surface density of the disk.

Speckle noise: A form of granular "noise" caused by aberrations in an optical system that can look like a point source or planet.

Spectroscopy: The process of dissecting electromagnetic radiation from an object into its component wavelengths.

Starshade: A design for an external occulter for space-based telescopes. The shade is positioned between a telescope and a target star system. The shade is used to block the light coming from the star in order to enable the detection of light from an exoplanet.

Sun-like stars: Main sequence stars with internal structures similar to the Sun and with spectral types ranging from mid-to-late F through K. These stars are considered distinct from M dwarfs for the purposes of this report.

Telluric: Of or relating to Earth; telluric "lines" refers to features from elements and molecules in Earth's atmosphere, and these may interfere with ground-based spectra of celestial objects.

Throughput: The ratio of incoming photons or flux from a point source, to those collected by the detector. Throughput can be degraded by elements such as a telescope central obscuration (support struts) and absorption by optical elements in the system.

Tidal locking: During long-term orbital interaction, when two co-orbiting bodies interact to drive the rotation rate of at least one of the bodies into a state where the orbital period is equivalent to, or an integer multiple of, the rotation rate.

Transit: The passage of an astronomical object across the face of one of larger angular diameter.

Volatile: A substance that vaporizes at a relatively low temperature.

Wavefront aberrations: The deviation or deformation of a wavefront from the desired formation, resulting in degradation of image quality. Aberrations disturb the convergence of energy to a point-image, which is the ideal outcome.

Weathering: The breaking-down of materials, through either physical or chemical forces. Physical processes include destruction through direct contact with abrasive forces, heat, or pressure. Chemical weathering is the breaking down of materials through chemical reactions, and examples include hydrolysis and oxidation.