Consensus Study Report

September 2018

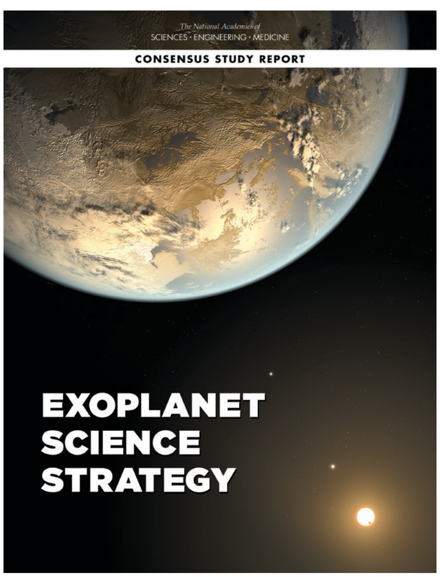
HIGHLIGHTS

Exoplanet Science Strategy

Is our solar system a cosmic rarity or a Galactic commonplace? How do Earth-like planets form and is there life on other worlds? What path should we take to answer these questions? At the request of NASA,[1] the National Academies of Sciences, Engineering, and Medicine developed a science strategy for the study of exoplanets (planets around other stars) in preparation for the upcoming decadal surveys in astronomy and astrophysics and in planetary science. *Exoplanet Science Strategy* identifies research priorities for the field of exoplanet science and makes recommendations for agency investments in key missions, facilities, and initiatives.

EXOPLANET SCIENCE SEEKS TO UNDERSTAND THE FORMATION OF PLANETS AND THEIR HABITABILITY

Over the past decade, exoplanet science has yielded many remarkable discoveries, from the direct imaging of young gas-giant exoplanets to the detection of molecules and clouds within the atmospheres of more than a hundred worlds. However, our knowledge of the full range of exoplanet characteristics, and that of their local environments, remains substantially incomplete.



The overarching goals of exoplanet science are twofold:

- To understand the formation and evolution of planetary systems and characterize the diversity of planetary system architectures, planetary compositions, and planetary environments; and
- To learn enough about the properties of exoplanets to identify potentially habitable environments and search for signatures of life on worlds orbiting other stars.

Advancing our understanding of the formation and evolution of planets requires surveying a wide variety of planet types (including protoplanetary disks, young planets, and mature planetary systems). Characterizing the masses, sizes, atmospheres, and compositions of a large number of exoplanets with a range of orbital parameters and a diverse set of parent stars will yield fundamentally new insights into the physics and chemistry of planetary environments.

[1] directed by the NASA Transition Authorization Act of 2017

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While the concept of the habitable zone (the area around a star where an Earth-like planet could support liquid water on its surface) has provided a useful guide of where to begin looking for habitable exoplanets, a multi-parameter holistic approach is ultimately required before selecting targets for biosignature searches. In addition, inferring the presence of life on an exoplanet from remote measurements will require a detailed understanding of the exoplanetary system and its local stellar environment as well as contingencies for identifying false negatives and false positives.

A SPACE-BASED EXOPLANET IMAGING MISSION IS NEEDED

Current and upcoming instruments such as the TESS (Transiting Exoplanet Survey Satellite) and JWST (James Webb Space Telescope) missions will find and study rocky planets orbiting nearby small stars. These observations are important for determining what types of planetary environments are likely to be habitable. The next step is for the exoplanet community to observe potentially habitable planets orbiting Sun-like stars to enable direct comparisons with our own solar system. Characterizing Earth-sized planets in habitable zones of Sun-like stars will require a space-based, direct-imaging mission employing either a coronograph or starshade to block out the light from the parent star. Such a mission will require bold investments and a longer timescale to bear fruit, but along the way it will advance our scientific knowledge and technological capacity.

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.

GROUND-BASED TELESCOPES WILL PLAY AN IMPORTANT ROLE

The ground-based, U.S.-led Giant Magellan Telescope (GMT) and Thirty Meter Telescope (TMT) will enable profound advances in the imaging and spectroscopy of entire planetary systems. Equipped with high-resolution optical and infrared spectrographs, GMT and TMT will be powerful tools for studying exoplanet atmospheres and have the potential to detect molecular oxygen in temperate terrestrial planets transiting the closest and smallest stars. However, investment is needed to enable the full science potential of GMT and TMT for studying exoplanets, while coordinating with existing U.S. facilities that can provide complementary observations and serve as proving grounds for new instruments.

RECOMMENDATION: The NSF should invest in both the GMT and TMT and their exoplanet instrumentation to provide all-sky access to the US community.

WFIRST WILL PROVIDE CRITICAL EXOPLANET DATA AND PAVE THE WAY FOR A DIRECT-IMAGING MISSION

A statistical census of the overall population of exoplanets will be essential to inform our understanding of planet formation. While previous exoplanet surveys such as the Kepler mission have characterized planets relatively close to their stars, our knowledge of planets in the outer reaches of planetary systems is woefully incomplete. The National Academies' 2010 Decadal Survey in Astronomy and Astrophysics realized this and strongly recommended the Wide-Field Infrared Survey Telescope (WFIRST) mission. WFIRST will be capable of performing a microlensing survey to provide data on planets with separations greater than the Earth-Sun distance and planets with masses greater than that of Earth. Previous and concurrent observations from other ground- and space-based facilities will help optimize and support the WFIRST microlensing survey.

WFIRST will also play an extremely valuable role in paving the way for a large direct-imaging mission. Flying a coronagraph capable of studying exoplanets on WFIRST will significantly advance the technology and reduce the risk for future missions seeking to employ this technique. The greatest value compared to ground testing will come from the observation and analysis of actual exoplanets, which will help test newly-developed algorithms and methods. WFIRST will also help characterize dust found in planetary systems that might pose issues for direct-imaging missions.

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

PRECISE RADIAL VELOCITY MEASUREMENTS WILL SUPPORT FUTURE EXOPLANET MISSIONS

Knowledge of a planet's mass (typically determined through radial velocity measurements) is essential to understanding its composition and atmosphere. Increasing the sensitivity of our radial velocity measurements to support future transiting and direct-imaging exoplanet missions is critical, especially if we seek to study Earth-like planets orbiting Sun-like stars. Progress will require new instruments installed on large telescopes, substantial amounts of observing time, and interdisciplinary collaboration.

RECOMMENDATION: NASA and NSF should establish a strategic initiative in Extremely Precise Radial Velocities to develop methods and facilities for measuring the masses of temperate terrestrial planets orbiting Sun-like stars.

JWST COULD SURVEY EXOPLANET ATMOSPHERES AND GUIDE FUTURE OBSERVING STRATEGIES

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

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

AN INTERDISCIPLINARY, ENGAGED COMMUNITY IS ESSENTIAL FOR EXOPLANET SCIENCE

The identification of life on an exoplanet will not be accomplished by a single team of researchers or a single method. It will happen only when we bring together the combined insights of astrophysicists, planetary scientists, Earth scientists, and heliophysicists, and provide them the opportunity and resources to collaborate. To address the profound scientific questions outlined in the study, agencies and organizations should continue to find novel ways to partner with each other on instruments, telescopes, or missions that are too ambitious or expensive for any individual agency to fund, build, and operate alone.

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.

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.

The search for life on other worlds is both a profound and a profoundly difficult endeavor, and the likelihood of success is maximized by marshalling, developing, and supporting all available talent. To the extent that discrimination and harassment, as known to exist in the greater scientific workforce, affect the exoplanet community, they will serve as barriers to the participation of people from certain demographic groups and limit the full application of talent. *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.

RELATED ACTIVITIES AND PUBLICATIONS

The 2020-2030 Decadal Survey on Astronomy and Astrophysics is now underway. Find out more on the study website at **nas.edu/astro2020**. For information about past decadal surveys, download the following publications:

New Worlds, New Horizons in Astronomy and Astrophysics - **nap.edu/12951**

New Worlds, New Horizons: A Midterm Assessment - **nap.edu/23560**

Vision and Voyages for Planetary Science in the Decade 2013-2022 - **nap.edu/13117**

Visions into Voyages for Planetary Sciences in the Decade 2013-2022: Midterm Review - **nap.edu/25186**

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