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Subcommittee on Space, Science, and Competitiveness
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Mr. Chairman and Members of the Committee, thank you for the opportunity to appear today to discuss scientific opportunities and NASA space science.

My name is Sara Seager and I am from the Massachusetts Institute of Technology where I am a Professor of Planetary Science, Physics, and Aerospace Engineering. I am a member of the National Academy of Sciences and a MacArthur Fellow. Currently I serve as the Deputy Science Director for the NASA mission Transiting Exoplanet Survey Satellite (TESS), Principal Investigator of the CubeSat Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA), and as a lead for the Starshade Rendezvous Mission (a space-based direct imaging exoplanet discovery concept under technology development). My research focuses on exoplanets and the search for life beyond Earth.

For thousands of years, since at least the time of the Greek philosophers people have wondered about planets and life beyond Earth, “Are we alone?” One of our Founding Fathers Thomas Paine commented, “The probability, therefore, is that each of these fixed stars is also a Sun, round which another system of worlds or planets, though too remote for us to discover, performs its revolutions, as our system of worlds does round our central Sun.” Another of our Founding Fathers, John Adams, shared astronomers’ speculation at the time, “Astronomers tell us, with good Reason, that not only all the Planets and Satellites in our Solar System, but all the unnumbered Worlds that revolve around the Fixt stars are inhabited, as well as this Globe of Earth.”[1]

Today we do not yet have evidence for life beyond Earth. We do know for certain that stars are suns. We know of thousands of planets orbiting other stars, called exoplanets. We know of a few dozen exoplanets that may have the right temperatures for life based solely on their distances from and heating by the host star (the “habitable zone”). We have a growing list of solar system bodies, including Mars, Europa, Enceladus, and others, that have evidence of subsurface liquid water. Because water is required for all life as we know it, these bodies might be able to support life. We are the first humans in history that have a chance to answer the compelling questions about whether there is life beyond Earth.

The Transiting Exoplanet Survey Satellite (TESS) is NASA’s new exoplanet discovery space mission. TESS launched on April 18, 2018 aboard a SpaceX Falcon 9 rocket out of Cape Canaveral Air Force Station. TESS will survey nearby stars for transiting exoplanets. Transiting exoplanets are those that pass in front of their parent star as seen from the telescope, a phenomena that is exploited as a planet discovery technique that NASA’s *Kepler* mission has used to discover thousands of exoplanets or planet candidates. TESS is

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[1] The Extraterrestrial Life Debate, Antiquity to 1915: A Source Book, M. J. Crowe

a NASA Explorer-class mission led by the Massachusetts Institute of Technology, with PI George Ricker. TESS carries four identical specialized wide-field CCD cameras (or telescopes), each with a 100-mm aperture and each covering 24° × 24° on the sky (equivalent to about 50 full Moons). In a two-year, nearly all-sky survey of the solar neighborhood, TESS will cover 400 times as much sky as NASA's *Kepler* mission did. In the process, TESS will examine millions of stars, including about half a million bright nearby targeted stars of prime interest, and likely find thousands of exoplanets with orbital periods (i.e., years) up to about 30 to 50 days.

The TESS spacecraft successfully entered its final lunar resonant orbit on 30 May 2018 (UTC). The TESS cameras are performing as planned, with on-orbit measured properties fully consistent with pre-launch measurements. The TESS mission has completed its commission activities for understanding instrument and spacecraft performance, and command and flight data handling pipelines.

TESS officially began science operations on July 25, 2018. TESS is expected to transmit its first series of science data back to Earth in August, and thereafter periodically every 13.7 days, once per orbit, as the spacecraft makes it closest approach to Earth. The TESS Science Team will begin searching the data for new planets immediately after the first data series arrives.

Out of the thousands of planets TESS is expected to discover, a special prized subset are the planets transiting in the habitable zone of small "red dwarf" stars. Red dwarf stars are half to one tenth the size of our Sun. In almost every possible way, a small planet orbiting a small star is far easier to detect and follow-up study than a small planet orbiting a larger Sun-like star. (Note that large planets (giant planets like Jupiter) are not considered in the search for life because they have immense atmosphere of hydrogen and helium, creating an interior too hot to support life). The TESS and other ground-based discovered planets transiting red dwarf stars will be suitable for atmosphere studies with the *James Webb Space Telescope* for similar reasons. The signature of a tiny atmosphere of an exoplanet is much larger (by up to 100 times) against the backdrop of a small red dwarf star compared to the backdrop of a star the size of our Sun.

The James Webb Space Telescope (JWST) is one NASA's most ambitious and technically complex missions, with ten new technologies. JWST is NASA, European Space Agency, and Canadian Space Agency collaboration and will be the premier astronomical observatory of the next decade. JWST's large collecting area (6.5-meter primary mirror), infrared capability, specialized instruments, and orbit location far from Earth's interference make it very suitable to carry out precision measurements on exoplanet atmospheres. Despite the delays and cost growth, the exoplanet community remains tremendously enthusiastic, because the JWST will provide our first capability to study exoplanets in the search for life. The JWST was conceived of before exoplanets had been discovered, and it is a testament to the power of NASA Flagship missions that JWST can be applied to the search for life on exoplanets.

JWST will be used to observe small exoplanet atmospheres, searching for key atmosphere component gases. The first is water vapor. On a small exoplanet water vapor is indicative of liquid water ocean reservoirs; again liquid water is needed for all life as we know it. Next are “biosignature gases”, gases that might be attributed to life’s production. Here we assume that, like life on Earth, life elsewhere uses chemistry to extract and store energy for later use, generating byproduct gases during metabolic processes. On Earth oxygen is the most robust “biosignature gas”. Filling our atmosphere to 20% by volume, oxygen is so reactive that without continual generation by plants and photosynthetic bacteria oxygen would not be present. Other gases produced by life on Earth include methane, nitrous oxide, hydrogen sulfide, and many others. Here I must emphasize that we will not know if any biosignature gases upon an exoplanet are produced by intelligent life or by simple single-celled bacteria. In order to associate biosignature gases with life on an exoplanets we must work to understand the false positive scenarios where the same gases might be produced by geophysics (such as volcanoes) or atmospheric chemistry. Associating gases with biological origin is a hefty and complicated endeavor, one that requires understanding the overall planet properties, planet atmosphere inventory including greenhouse gases, and host star radiation incident on the planet.

JWST will exploit transiting planets. As a transiting exoplanet passes in front of its host star, JWST can observe the exoplanet's atmosphere, as it is backlit by the star, if the star is bright enough. Additional atmospheric observations can be made by observing as the exoplanet disappears and reappears from behind the star. In these observations the exoplanets and their stars are not spatially separated on the sky but are instead observed in the combined light of the planet-star system.

Planets orbiting red dwarf stars are truly a frontier for discovery. Because red dwarf stars have a small energy output, a habitable-zone planet must orbit very close to its star in order to have the proper temperature for liquid water. Being close to the star means the star may loom very large in the sky. The star (i.e., the sun) would be in the same place in the sky at all times; the planet will have a permanent day- and night-side. The cause is the huge gravitational force from the star that over time would have forced the nearby planet into a “tidally-locked” state, where the planet shows the same face to the star at all time, just like the Moon does to Earth. A year on the planet (the time it takes the planet to orbit once around the star) would be equivalent to a few Earth days to weeks. More seriously, harmful ultraviolet radiation and huge flares of energy typical for red dwarf stars would frequently bathe the planet’s surface. We humans could not tolerate the severe radiation which would disable electronics and power grids and even destroy biological cells. Because simple life forms on Earth can survive extreme environments of temperature, acidity, radiation, and many other environmental factors, life may also survive the extreme environments on planets orbiting red dwarf stars.

The Path for Discovering a True Earth Twin The ultimate goal in the search for life on exoplanets is to find a true Earth twin in an Earth-like orbit about a *Sun-like star* (Earth analog). A planet like Earth with a thin atmosphere and water oceans, whose environment we will be predisposed to understand and identify life in context with. JWST will not help because first, planets in Earth-like orbits have an extremely low probability to transit

(1/200) and second an Earth-sized atmosphere signal against the backdrop of the relatively large Sun-sized star is too small for JWST to observe. To find an Earth analog, we need a different technique, one that astronomers call direct imaging where the starlight is blocked so we can see the planet directly.

The immense direct imaging challenge is that an Earth-like exoplanet is adjacent to a parent star that is up to 10 billion times brighter than the planet itself. The challenge is likened to the search for a firefly in the glare of a searchlight, when the firefly and searchlight are about 2,500 miles distant, such as the separation between Washington, D.C. and the west coast of the United States. Direct imaging to find and characterize small exoplanets requires space telescopes above the blurring effect of Earth's atmosphere.

The Coronagraph is one NASA-supported technique for direct imaging for Earth analogs, where specialized optics are placed inside a space telescope to block out the parent starlight and reveal the presence of any orbiting exoplanets. The telescope must be highly specialized, with an observatory system that has exceptional thermal and mechanical stability. Tiny telescope imperfections that scatter starlight can be canceled out using a small mirror with thousands of adjustable elements. The corrections are equivalent to the telescope's primary mirror being smoothed to sub nanometer levels, a dimension many thousands of times smaller than the width of a human hair. Such control has already been demonstrated in a laboratory vacuum test setup, at the instrument subsystem level. The Jet Propulsion Laboratory's High Contrast Imaging Testbed has achieved starlight suppression of 5×10^{-10} at visible wavelengths (10% bandpass), in a static demonstration.

The Wide-Field Infrared Survey Telescope (WFIRST) Coronagraph Instrument (CGI)
WFIRST is a NASA space-based observatory designed to address key questions in infrared astrophysics, dark energy science, and exoplanet detection, including an exoplanet microlensing discovery survey to further an exoplanet population census. The WFIRST observatory has a 2.4-m diameter primary mirror and two instruments and will operate in six-year planned mission duration. WFIRST was prioritized by the 2010 Decadal Survey, and is being developed for launch in the mid-2020s to orbit at the second Sun-Earth Lagrange point (L2). Phase B of development began in April 2018.

The WFIRST Coronagraph Instrument (CGI) is being built as a technology demonstration for high-contrast direct imaging. As the first ever high-contrast space-based coronagraph, the CGI will flight-qualify the high-contrast coronagraph's key components. GCI will demonstrate technologies such as wavefront control and understanding the effect of telescope stability in a space environment on high-contrast coronagraphic images.

The WFIRST CGI is designed to meet its Level 1 requirement for planet-star flux contrast levels of 5×10^{-8}. While such levels would not reach down to the planet-star flux ratios required to observe Earth-sized exoplanets (better than one part in ten billion (10^{-10})), CGI will be able to perform high-contrast direct imaging or spectroscopy of up to a dozen already known giant exoplanets systems in reflected light, as well as study the potentially contaminating light from zodiacal dust around nearby stars.

At its current level of predicted performance, and with the ability to obtain spectra of known giant exoplanets, the WFIRST CGI remains critical to increase the technology readiness level and decrease risk for future ambitious space-based direct imaging mission concepts now under study by NASA, such as the Habitable Exoplanet Imaging Mission (HabEx)[2] and the Large UV Optical Infrared Surveyor Large Ultraviolet Visible and InfraRed Surveyor (LUVOIR)[3].

The Starshade (or external occulter) is a second NASA-supported technique for direct imaging of Earth-sized planets in Earth-like orbits about Sun-like stars. A starshade is a carefully shaped screen with its own spacecraft and flown in formation with a telescope. The starshade size and shape, and the starshade-telescope separation are designed so that the starshade casts a very dark, and highly controlled equivalent of a shadow, where the light from the star is suppressed while leaving the planet's reflected light unaffected; only the exoplanet light enters the telescope. Most designs feature a starshade tens of meters in diameter, and separated from the telescope by tens of thousands of kilometers.

The starshade concept is so powerful because within a decade, a starshade mission with a modest-sized telescope could discover the first Earth-like exoplanets orbiting Sun-like stars and obtain spectra of their atmospheres. The reason a starshade and modest telescope can reach an Earth-like planet discovery is because the starlight blocking is done by the starshade, outside of the telescope itself. The telescope system can therefore be relatively simple, one without any stringent requirements on the optical quality of the telescope; since no starlight enters the telescope; no advanced wavefront sensing technology and control is necessary. The telescope can be designed for very high throughput and the starshade would have a very broad wavelength bandpass for blocking out the starlight. These two key features (throughput and starshade bandpass) are unique amongst starlight suppression techniques, and enable high sensitivity spectroscopy for characterization at planet-star contrasts of one part in ten billion with a modest telescope. A starshade must maneuver across the sky for each new target star; the number of nearby target stars available for a starshade mission with a modest telescope is well matched to the number of starshade retargeting maneuvers, mitigating the main starshade challenge of repositioning for target stars.

In 2013 NASA commissioned a study team "Exo-S" to examine a Probe-class mission using a starshade with a modest telescope and with a target cost guideline of $1B. The Exo-S Team studied two viable starshade-telescope missions[4]. First, a starshade and telescope system dedicated to each other for the sole purpose of direct imaging for exoplanets. The starshade and commercial 1.1-m diameter mirror telescope would co-launch, sharing the same low-cost launch vehicle, conserving cost. The "Dedicated" mission would orbit in a heliocentric, Earth leading, Earth-drift away orbit, away from the gravity gradient of Earth orbit which is unsuitable for formation flying of the starshade and telescope. The telescope would have a conventional instrument package that includes the planet camera, a basic spectrometer, and a guide camera. The second Exo-S mission

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[2] Habitable Exoplanet Imaging Mission (HabEx)." https://www.jpl.nasa.gov/habex/

[3] Large UV/Optical/IR Surveyor (LUVOIR) https://asd.gsfc.nasa.gov/luvoir/

[4] Starshade Probe 2015 Report https://exoplanets.nasa.gov/internal_resources/788

concept studied was a starshade that would launch separately to rendezvous with an existing on-orbit space telescope (the “Starshade Rendezvous Mission”). The existing telescope adopted for the study was WFIRST.

Both Exo-S starshade concept science cases envision a focus on our nearest Sun-like star neighbors, scouring the systems for all of their contents. An estimated few dozen exoplanets including a few Earth-sized exoplanets in Earth-like orbits would be newly discovered. Only the larger aperture telescope would be capable of obtaining atmosphere spectra for most of the discovered Earth-size exoplanets. Studies to advance the science case, risk, and cost assessment for a range of starshade mission options are ongoing.

Originally conceived of in the 1960s, and revisited each decade since, starshade technology now heavily builds upon deep industrial heritage of large space-based deployable radio antennas. Because the burden of starlight suppression is on the starshade, no new technologies for the space telescope are needed. To reach the required starlight suppression, tolerances of hundreds of microns for starshade petal shape, tens of mm for petal positioning, and formation flying to 150 km along the line of sight and meters laterally are needed. So far, technology milestones include subscale demonstrations, precision manufacturing of starshade petal edges, and starshade occulter stowage and deployment. Current lab-based experiments have demonstrated dark shadows within about an order of magnitude of what is required in space.

A directed effort to mature five different starshade technologies was created by NASA’s Astrophysics Division in March 2016 (called “Starshade to TRL 5” or S5), though shorter timescales are possible with more funding. S5 will mature key technologies to TRL 5 by 2023 in order to be ready for a possible mission opportunity later in the decade. A starshade with WFIRST would be the first mission opportunity, increase the technology readiness level and decrease risk for future ambitious space-based direct imaging mission concepts now under study by NASA, such as the Habitable Exoplanet Imaging Mission (HabEx)[3].

The Starshade with WFIRST concept envisions a starshade launched shortly after WFIRST and rendezvousing with it at L2. NASA headquarters has directed the WFIRST project to accommodate the needed hardware and software required to make WFIRST operational with a starshade and the associated costs through 2020 are borne by the WFIRST project. Later costs would be carried by the starshade project, pending a Decadal Survey recommendation. The impact on WFIRST for starshade readiness is minimized because the existing coronagraph instrument will perform as the starshade science instrument, while formation guidance will be handled by the existing coronagraph focal planes with minimal modification. The telescope spacecraft must also carry some specific hardware needed for formation flying, a starshade acquisition camera and an interspacecraft radio link for spacecraft-to-spacecraft communications for formation flying. These additions are straightforward because no new technologies are needed. The starshade program would use a small amount of WFIRST observatory time (on order 9%). The 2015 Aerospace Corporation-validated cost estimate for the starshade and spacecraft is $630 M[4].

Value in the Search for Life Beyond Earth NASA missions inspire the next generation to study STEM fields and enter STEM careers outside of academic research. My science and engineering students at MIT and elsewhere crave to work on challenging and meaningful technical problems, and few if any efforts are more attractive in this regard than the search for life beyond Earth using advanced space missions. Many students who completed studies or leave academic research careers in space science and engineering use their advanced technical skills in many other areas, including aerospace technology development, remote sensing, and data sciences including artificial intelligence and machine learning in a wide range of commercial industries. Furthermore, people trained in space sciences and engineering gain the technical skills relevant for work on national defense and national security issues. As a nation we must continue to be bold in our space endeavors, so as to not only inspire the next generation but also to keep a skilled workforce at the forefront of technology.

Our drive to explore space has yielded many practical discoveries, in medicine, transportation, chemical detection, consumer products and more. My team's space satellite, the ASTERIA 6U CubeSat implemented and operated by the Jet Propulsion Laboratory has demonstrated precision pointing in small package, reaching 100 times better pointing than anything in its mass category. While initially intended as a prototype for a fleet of satellites for exoplanet discovery, ASTERIA's precision pointing legacy will more likely be in more practical satellite applications. For example, for space situational awareness satellites (e.g., small satellites observing from low Earth orbit). Another example is optical communication (using visible light waves which can carry more information than radio waves but requires precise pointing) both by conventional low Earth orbit satellites and also for deep space commercial insitu space resource utilization (such as asteroid mining) for which commercial companies will need their own space-based communication networks.

NASA is a global leader in space science. The Starshade Mission—our best, first path to finding another Earth with signs of life—is only being developed in the United States of America. Prioritizing among NASA's many important missions is never easy, both Congress and the astronomy and planetary science community will have to make tough choices if we are to lead the way and be the first to discover signs of life beyond Earth.

Mr. Chairman and Committee this concludes my remarks. Thank you for your attention and your continued support for NASA's space science missions for revolutionary new discoveries.