Statement of Dr. Jacob L. Bean

Assistant Professor of Astronomy & Astrophysics
University of Chicago

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Mr. Chairman and Members of the Committee, thank you for giving me the opportunity to serve as a witness for this important hearing. My testimony today will be focused on the topic of exoplanet atmosphere spectroscopy in the context of the search for life beyond Earth. The main point I want to convey is that a deliberate, comprehensive, and robust exoplanet exploration program with a *Terrestrial Planet Finder* telescope as its centerpiece could answer one of humanity's most fundamental questions: is there life elsewhere in the Universe? Pursuing this program now would leverage significant momentum built up over the past two decades in the field of exoplanets, extend US leadership in space exploration, and leave a legacy of immeasurable value for our children and future generations.

Current status of efforts to find Earth-like planets beyond the Solar System

Extrasolar planets, or "exoplanets" for short, are planets outside our Solar System that orbit stars other than our Sun. The study of exoplanets has recently emerged as one of the most exciting areas of scientific research as evidenced by the popularity of the subject with the public and increased interest by students at our universities. This year marks just the 20th anniversary of the first detection of an exoplanet orbiting a Sun-like star, but progress in the field has been rapid in the intervening years. For example, exoplanet surveys during this short time period have been amazingly successful at revealing the frequency of planets of different sizes and orbital distances. These data provide constraints on models of planet formation, and the discovery of thousands of exoplanets with a diverse array of properties has been the genesis for revolutionary new ideas about the origins of our own Solar System.

Progress in the field of exoplanets has accelerated in the last few years due to improved technology. In particular, the launch of NASA's *Kepler* telescope in 2009 has revolutionized the field. The *Kepler* mission and a few other surveys using ground-based telescopes have advanced to the point that they are now focused on finding Earth-size planets orbiting their host stars in the so-called "habitable zone", which is the distance at which the temperature on the surface of a terrestrial planet could conceivably be right for liquid water to be present. A handful of Earth-size habitable-zone exoplanets have been found over the last few years. These discoveries have grabbed the attention of the broader scientific community and they have sparked the imagination of the public because they suggest that Earth-like planets exist around relatively nearby stars, and that we therefore have it within our grasp to search for life on other worlds.

Why exoplanet characterization through atmospheric spectroscopy is important

The discovery of habitable-zone exoplanets has been one of the long-standing goals of the field since its inception. With this aim now being realized we are in a position to take the next step towards determining if any of these planets are truly habitable and even inhabited. This next step is to study exoplanet atmospheres using the technique of astronomical spectroscopy.

Planetary atmospheres are a key factor in the question of habitability. They are essential for life as reservoirs of biogenic elements, media for chemical reactions, and regulators of planetary surface conditions. Planetary atmospheres can in turn be influenced by interactions with a biosphere, and thus may be a marker of life itself absent direct observation or communication.

Astronomical spectroscopy is the only way that we can reveal the fundamental properties of exoplanet atmospheres for the foreseeable future. Astronomers have begun to reveal the nature of the atmospheres of hot, gas giant exoplanets using the *Hubble* and *Spitzer Space Telescopes* and the ground-based Keck and Gemini telescopes. These investigations have yielded constraints on the abundances of key chemical species like water, carbon monoxide, methane, and sodium, the identification of clouds, and determinations of temperature maps.

We do not currently have telescopes that are capable of making meaningful spectroscopic observations of exoplanets that might resemble the Earth. Therefore, we do not yet know anything about the nature of the atmospheres surrounding the habitable-zone exoplanets that have been discovered, and we do not yet know if there are any other Earth-like planets. However, in the process of studying the extreme worlds that are within reach of existing instruments, astronomers are honing the techniques that could be used to study candidate Earth-like planets with future facilities.

What is needed to find and understand the existence of life on exoplanets

Astronomers have a solid understanding of what observations should be done to characterize the atmospheres of candidate Earth-like planets that is built on the knowledge gained from the exploration of the Solar System planets and Earth-observing satellites. Spectroscopic observations of these planets would reveal the compositions, thicknesses, and temperatures of their atmospheres. Combined with knowledge of the planets' orbits and host star properties, theoretical models could then be used to determine if liquid water is likely to exist on the surface.

Furthermore, spectroscopic observations of candidate Earth-like exoplanets have the potential to reveal the presence of so-called "biosignature gasses", which are chemical species that can only be produced in large quantities in a planetary atmosphere by living organisms. Consensus opinion in the astrobiology community is that molecular oxygen (O_2) and its photochemical byproduct ozone (O_3) are the most robust biosignatures in the atmosphere of a planet like the Earth. However, interpretation of biosignatures in isolation runs the risk of a false positive detection of life given our inability to predict the diversity of planetary atmospheres. Therefore, we must also determine the abundances of all the major molecules in a planet's atmosphere to interpret the detection of biosignatures using the universal laws of physics and chemistry. For example, the remote detection of molecular oxygen or ozone in combination with methane in the Earth's atmosphere would be strong evidence for life on our planet because chemical reactions would quickly deplete these species if they weren't constantly being replenished.

Prospects for characterizing candidate Earth-like planets in the next ten years

Astronomers eagerly await the launch of the *James Webb Space Telescope* (*JWST*) in 2018. Among its many new important capabilities, the wider wavelength range, higher spectral resolution, and higher precision possible with *JWST* compared to existing capabilities will dramatically extend the reach of exoplanet spectroscopy. This will enable more detailed investigations of the hot, giant planets currently being studied, and it will also enable the push towards characterizing the more numerous smaller and cooler planets that have been revealed in abundance by the *Kepler* mission.

It may even be possible to begin studying the atmospheres of potentially habitable worlds with *JWST*. The NASA missions *K2* (ongoing) and *TESS* (to be launched in 2017) and other surveys will likely discover the first habitable-zone Earth-size planets orbiting low-mass stars that are feasible for characterization over the next five years. *JWST* will probably have the ability to determine the presence of major molecules like water and carbon dioxide in these planets' atmospheres and measure their temperatures. However, *JWST* will be hard-pressed to detect biosignatures, only made possible with fortuitous planets, extraordinary performance of the instrument, and large amounts of biosignature gasses in the planets themselves.

A vision for the future: towards a Terrestrial Planet Finder

The combination of *K2/TESS* and *JWST* will be powerful for making a first study of potentially habitable worlds, but it will not yield data for Earth-like planets around Sun-like stars. True Earth analogs around Sun-like stars are the holy grail of scientists' exoplanet astrobiology ambitions because this is the only class of planets with a known habitable example and because we want to understand our planet in a cosmic context.

A flagship space telescope with next generation optics will be needed to detect life on Earth-like planets. Astronomers commonly refer to telescope concepts with this capability as a "*Terrestrial Planet Finder*" (*TPF*). A decade ago NASA had plans for an exoplanet exploration program that included three major space telescopes that would search for and characterize Earth analogs around nearby stars. This program included two *TPF* missions with complementary capabilities for searching for biosignature gasses. These missions were cancelled for budgetary reasons, but the fundamental principles that they were based on remain true.

The astrophysics community is currently ramping up for a Decadal Survey (report to be released in 2020) that will prioritize large space missions to follow *JWST*. The stunning success of the *Kepler* mission has reinvigorated the search for other Earths and *TPF*-type telescopes of different scales and capabilities will be discussed during the Decadal process. However, the specter of budgetary constraints will loom large over these deliberations. The Decadal Survey committee may face the difficult decision of whether to prioritize a full-scale *TPF* mission at the expense of programatic balance given the expected astrophysics funding profile.

One of the challenges faced previously by the *TPF* program was that the original telescope concepts were expensive and narrowly focused. It is possible that a new *TPF*-type program could take advantage of synergies and new technology to cover a wider range of science. At the wise urging of NASA leadership, the community is currently studying how a *TPF* telescope could also be used for other topics in astrophysics and planetary science. One strawman concept[1] is for a large, single aperture telescope (12 meter diameter primary mirror size, compared to *Hubble*'s 2.4 m and *JWST*'s 6.5 m primary mirrors) operating from the ultraviolet to near-infrared wavelength regimes. This wavelength range is similar to that currently spanned by *Hubble*, and so this new telescope would enable substantial new science in a similarly broad range of areas (e.g. the formation and evolution of galaxies, the origins of the chemical elements, and the life cycles of stars) if it were equipped with appropriate instruments.

In addition to general purpose instruments for a wide range of astronomy, the new telescope would have to be equipped with a dedicated planet imaging system to find and characterize Earth-like planets. A major component of the planet imaging system would be an occulter to block the blinding light of the stars that the planets orbit. The occulter may be either inside the imaging instrument (an internal occulter, or "coronograph") or outside the telescope itself (an external occulter, or "starshade"). The basic idea of the coronograph is similar to the original *TPF-C* concept. On the other hand, the idea for a starshade is new since the original *TPF* missions were developed. The starshade concept involves an occulter flying free of the telescope spacecraft, but precisely aligned with the telescope optics tens of thousands of miles away.

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[1] See the "High-Definition Space Telescope" concept that is discussed in a recent report by a committee commissioned by the Association of Universities for Research in Astronomy (AURA) at http://www.hdstvision.org.

The top priority from the previous Decadal Survey, currently dubbed "*WFIRST-AFTA*", will have capabilities that lay a foundation for *TPF*. One of the science goals of the mission is to take a census of planets in the outer parts of planetary systems similar to that obtained by the *Kepler* mission for the inner regions. The orbital separation parameter space covered by *Kepler* and *WFIRST-AFTA* will overlap for planets in Earth-like orbits. Therefore, we will get improved statistics on the frequency of potentially habitable planets from this new mission.

Furthermore, NASA is currently considering including a planet imager on *WFIRST-AFTA*. This would be an important step towards a *TPF* mission because it would inaugurate the specific kind of exoplanet spectroscopy that we one day hope to do for Earth-like planets (visible wavelength reflected light spectroscopy on resolved images) and serve as a technology demonstrator. The inclusion of a planet imager on *WFIRST-AFTA* wasn't envisioned by the Decadal Survey, but was made possible by the recent transfer of the *Hubble*-quality optics from the National Reconnaissance Office to NASA. Both a coronograph and a starshade are being studied as possibilities for the occulter that would be used for this mission.

In addition to getting buy-in from a wider scientific community in the US, it may also be possible to partner with appropriate international partners to share the cost of a *TPF*-type mission. This has been highly successful for the *Hubble* and *James Webb* telescope programs, among others. Europe in particular has previously considered their own version of a *TPF* mission, called *Darwin*. Nevertheless, I believe that US leadership for a *TPF* program is absolutely essential, just as it was and is for *Hubble* and *Webb*.

I have so far focused on a *TPF* mission in this vision for the future because this is the most important and challenging facility for addressing the question of life on other planets. However, *TPF* cannot be a success in the absence of other projects. To properly interpret the spectra of Earth-like planets we also must know the masses and orbits of these planets and the other planets that exist in the same systems, the properties of the host stars, and the nature of any asteroid and Kuiper belt analogs that may also be present. Beyond this, we need a deeper understanding of the origins of planetary systems that is based on knowledge of planet frequency and observations of young stars and their natal disks. These investigations require, at a minimum, continued support of many existing facilities (e.g., large ground-based optical/infrared telescopes and the ALMA radio telescope) and, ideally, construction of new facilities (e.g., new instruments for existing ground-based telescopes, a new generation of large ground-based telescopes like the Giant Magellan and Thirty Meter Telescopes, and other space missions beyond those already mentioned).

The need for comprehensive knowledge to confront the question of life on other planets is why I think a program in exoplanet exploration that encompasses observations with an array of facilities and a robust theory program to support the interpretation of the resulting data would be the best way forward. Although a *TPF* telescope would be the crown jewel, this program should be driven by the question of life rather than by a single facility. It would take courage and perseverance by scientists, representatives in government, and the public to act on this vision and see it through, but our ability to rise to this kind of challenge is part of what makes American exceptional. From the Apollo program, through the *Voyager*, *Hubble*, and Mars rover programs, and today with the launch of *JWST* just a few years away, our country leads the way in space projects that are lasting milestones of human exploration. The search for life beyond our planet represents the next great space exploration challenge that would continue this legacy.

Mr. Chairman and Members of the Committee, this concludes my remarks. Thank you again for the opportunity to testify and I remain at your service to answer questions.