ASTROBIOLOGY: SEARCH FOR BIOSIGNATURES IN OUR SOLAR SYSTEM AND BEYOND

HEARING

BEFORE THE

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HOUSE OF REPRESENTATIVES

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December 4, 2013

ASTROBIOLOGY: SEARCH FOR BIOSIGNATURES IN OUR SOLAR SYSTEM AND BEYOND

WEDNESDAY, DECEMBER 4, 2013

HOUSE OF REPRESENTATIVES,
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Committee met, pursuant to call, at 10:05 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Lamar Smith [Chairman of the Committee] presiding.

LAMAR S. SMITH, Texas
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Congress of the United States
House of Representatives

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Astrobiology: Search for Biosignatures in our Solar System and Beyond

Wednesday, December 4, 2013
10:00 a.m. to 12:00 p.m.
2318 Rayburn House Office Building

Witnesses

Dr. Mary Voytek, Senior Scientist for Astrobiology, Planetary Science Division, National Aeronautics and Space Administration

Dr. Sara Seager, Class of 1941 Professor of Physics and Planetary Science, Massachusetts Institute of Technology

Dr. Steven Dick, Baruch S. Blumberg Chair of Astrobiology, John W. Kluge Center, Library of Congress

U.S. House of Representatives
Committee on Science, Space, and Technology

HEARING CHARTER

Astrobiology: The Search for Biosignatures in our Solar System and Beyond

Wednesday, December 4, 2013
10:00 a.m. – 12:00 p.m.
2318 Rayburn House Office Building

Purpose

The purpose of this hearing is to examine astrobiology research and the search for biosignatures in our Solar System and beyond. The hearing will include a general assessment of the multi- and interdisciplinary nature of astrobiology research, including the role astrobiology plays in formulating NASA space missions. It will also examine the techniques and capabilities necessary to determine the potential for the existence of biosignatures within our Solar System. With the discovery of potential Earth-like planets outside of our Solar System, the hearing will also investigate what methods are being used to determine if any of these planets may harbor life. The hearing will explore existing and planned astrobiology research strategies and roadmaps.

WITNESSES:

- **Dr. Mary Voytek**, Senior Scientist for Astrobiology in the Science Mission Directorate at NASA headquarters

- **Dr. Sara Seager**, Professor of Physics and of Planetary Science at M.I.T. and 2013 recipient of a MacArthur Foundation "Genius Grant" for her work in exoplanet research

- **Dr. Steven J. Dick**, Baruch S. Blumberg Chair of Astrobiology, John W. Kluge Center, Library of Congress

Background:

The United States pioneered the field of astrobiology, and currently leads the world in astrobiology research. Astrobiology is multi-disciplinary and inter-disciplinary and attracts physicists, organic chemists, biologists, geologists and astronomers, among others from around the world to the United States to conduct their research. While conducting research, individual scientists must verse themselves in a variety of scientific disciplines, while also collaborating with colleagues across scientific fields. Astrobiologists study microbial life in underwater lakes beneath Antarctica, living organisms that can thrive in extreme temperatures at the edge of volcanic fissures on the bottom of the ocean and bacteria that live in deserts in order to better understand the varied conditions in which life might exist in the diverse environments on planetary bodies in our Solar System and beyond.

In their 2008 *Assessment of the NASA Astrobiology Institute*, the National Academies of Science collected several definitions of astrobiology from scientists. They found that it "is variously defined as the study of the origin, evolution, distribution, and future of life in the universe; the study of life as a planetary phenomenon; the study of the living universe; or the origin and co-evolution of life and habitable environments."[1]

Our Solar System

Astrobiology has been a part of space missions almost from the beginning of the space program. Current and future proposed space science missions within our Solar System incorporate astrobiology research, including the Mars rovers and orbiters, Cassini's fly-by examination of Saturn's moon Enceladus and proposed robotic missions to the Jupiter moons of Europa and Titan, in addition to many other missions.

Beyond Our Solar System

Astrobiologists and astrophysicists work together to discover and categorize exoplanets beyond our Solar System. The first definitive exoplanet discovery occurred in 1992.[2] On September 29, 2010, the Keck Observatory announced that it had identified the first Earth-sized planet orbiting a star in a "habitable zone," an area where a planet's distance from its sun increases the possibility it could have surface temperatures that could support the existence of liquid water.[3] On April 18, 2013, NASA's Kepler mission released details of its discovery of two new planetary systems that include three super-Earth sized planets in the "habitable zone."[4] On November 4, NASA announced that a review of Kepler's data from the past three years showed that there are over 3,500 potential exoplanets in our galaxy, 647 of them located in the "habitable zone."[5] The data also led scientists to estimate that there could be 140 billion planets in the Milky Way galaxy. One of these planets is 12 light years away.[6]

[1] National Research Council of the National Academies. *Assessment of the NASA Astrobiology Institute.* 2008. http://www.nap.edu/catalog/12071.html
[2] http://tech.mit.edu/V114/N22/psr.22w.html
[3] http://www.keckobservatory.org/recent/type/news//keck_observatory_discovers_the_first_goldilocks_exoplanet/
[4] http://www.nasa.gov/mission_pages/kepler/news/kepler-62-kepler-69.html
[5] http://www.scientificamerican.com/article.cfm?id=kepler-telescope-earth-sized-planets
[6] Ibid

NASA's Astrobiology Program

In the 1960, NASA established a formal astrobiology program. Currently, NASA's astrobiology program resides in the Planetary Science Division of the Science Mission Directorate, and includes four divisions:[7]

- *NASA Astrobiology Institute (NAI)* - In 1998, the NAI was established to coordinate and organize the various astrobiology research activities NASA funds. Scientific teams competed for NASA funding, and the 11 teams that were selected formed the first NAI through cooperative agreements between NASA and the teams' institutions. This structure remains today.
- *Exobiology and Evolutionary Biology (EXO)* – Supports research on the following topics: identification of habitable planets; how complex organic molecules travel between planetary bodies; and the study of potential planetary conditions suitable for organic life.
- *Astrobiology, Science and Technology Instrument Development (ASTID)* – Supports instrument development for use in astrobiology research on space flight missions and Earth-based experiments; contributes concepts to planetary exploration missions and small science payloads.
- *Astrobiology Science and Technology for Exploring Planets (ASTEP)* – Contributes to the development of technology that will foster the search for life in planetary bodies within and without the Solar System, including the design of *in situ* laboratories and sample analysis and return techniques.

Astrobiology Roadmap

In the past decade, NASA has published two Astrobiology Roadmaps, approximately five years apart. The last roadmap was published in 2008, and the next roadmap is expected to be published in 2014. The purpose of the roadmap is to outline definitions, goals, accomplishments and public outreach and education objectives in the field of astrobiology.

Each roadmap focuses on three essential questions:

- How does life begin in the universe?
- Does life exist elsewhere in the universe?
- What is the future of life on Earth and beyond?

[7] http://astrobiology.nasa.gov/

The 2008 roadmap includes seven science goals for the astrobiology community:[8]

- Understand the nature and distribution of habitable environments in the universe. Determine the potential for habitable planets beyond the Solar System, and characterize those that are observable.
- Determine any past or present habitable environments, prebiotic chemistry, and signs of life elsewhere in our Solar System. Determine the history of any environments having liquid water, chemical ingredients, and energy sources that might have sustained living systems. Explore crustal materials and planetary atmospheres for any evidence of past and/or present life.
- Understand how life emerges from cosmic and planetary precursors. Perform observational, experimental, and theoretical investigations to understand the general physical and chemical principles underlying the origins of life.
- Understand how life on Earth and its planetary environment have co-evolved through geological time. Investigate the evolving relationships between Earth and its biota by integrating evidence from the geosciences and biosciences that shows how life evolved, responded to environmental change, and modified environmental conditions on a planetary scale.
- Understand the evolutionary mechanisms and environmental limits of life. Determine the molecular, genetic, and biochemical mechanisms that control and limit evolution, metabolic diversity, and acclimatization of life.
- Understand the principles that will shape the future of life, both on Earth and beyond. Elucidate the drivers and effects of microbial ecosystem change as a basis for forecasting future changes on time scales ranging from decades to millions of years, and explore the potential for microbial life to survive and evolve in environments beyond Earth, especially regarding aspects relevant to US Space Policy.
- Determine how to recognize signatures of life on other worlds and on early Earth. Identify biosignatures that can reveal and characterize past or present life in ancient samples from Earth, extraterrestrial samples measured in situ or returned to Earth, and remotely measured planetary atmospheres and surfaces. Identify biosignatures of distant technologies.

The 2014 roadmap is expected to assess how well the astrobiology program has accomplished these goals, how the field has grown and evolved and what its focus should be in the coming years.

[8] https://astrobiologyfuture.org/resources/7

Chairman SMITH. The Committee on Science, Space, and Technology will come to order.

Welcome to today's hearing titled "Astrobiology: the Search for Biosignatures in our Solar System and Beyond." I will recognize myself for five minutes for an opening statement and then recognize the Ranking Member.

The search for exoplanets and Earth-like planets is a relatively new but inspiring area of space exploration. Scientists are discovering solar systems in our own galaxy that we never knew existed. As we learn more about these new worlds, reasonable questions to ask are: what can we find on these planets? Do the atmospheres of these planets provide biosignatures that would indicate the presence of some form of rudimentary life? And what would be the implications of such a discovery?

The discovery of even microbes on another planet would be the most newsworthy story in decades. It could affect the way we view our place in the universe and it could create increased interest in the core disciplines of astrobiology including chemistry, physics, geology and biology.

The United States has pioneered the field of astrobiology and continues to lead the world in this type of research. The publication of scientific findings illustrates the field's growth and growing popularity in the past 20 years.

A sample of professional papers published in Science magazine between 1995 and 2013 shows significant growth in the field of astrobiology. For example, in 1995, fewer than 50 papers were published on astrobiology. By 2012, that number had increased to more than 500. In 1995, fewer than 500 scientific reports cited astrobiology, but by 2012, it was almost 12,000.

Astrobiologists study the atmospheres of planets to determine whether or not some of these newly discovered planets possess possible signs of life such as microbes or some form of vegetation. Scientists believe that such planets would produce certain gases in their atmospheres. For example, when examined from a distance, Earth's atmosphere contains large amounts of oxygen. When looked at through a large infrared telescope, the biosignature would be detectable from a distant point in space.

Using the infrared camera on the Hubble Space Telescope, two teams of scientists from the University of Maryland, NASA's Goddard Space Flight Center, and the Space Science Telescope Institute announced just yesterday that they had found signatures of water in the atmospheres of five exoplanets. The planets are similar to what are called hot Jupiters, too large and gaseous to contain any form of known life. However, the techniques used in this case are also being used to examine the atmospheres of other planets.

Future telescopes, including the James Webb Space Telescope, the Transiting Exoplanet Survey satellite, and the Wide Field Infrared Survey Telescope will help us discover more about the atmospheres of exoplanets and whether or not microbes or other forms of life could exist there.

I look forward to hearing how research in astrobiology continues to expand this fascinating frontier.

That concludes my opening statement.

[The prepared statement of Mr. Smith follows:]

PREPARED STATEMENT OF CHAIRMAN LAMAR S. SMITH

Chairman Smith: Good morning. The search for exoplanets and Earth-like planets is a relatively new but inspiring area of space exploration. Scientists are discovering solar systems in our own galaxy that we never knew existed.

As we learn more about these new worlds, reasonable questions to ask are: What could we find on these worlds? Do the atmospheres of these worlds provide biosignatures that would indicate the presence of some form of rudimentary life? And what would be the implications of such a discovery?

The discovery of even microbes on another planet would be the most newsworthy story in decades.

It could affect the way we view our place in the universe. It could create increased interest in the core disciplines that fall under the umbrella of astrobiology, including chemistry, physics, geology and biology.

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I look forward to hearing how research in astrobiology continues to expand this fascinating frontier.

Chairman SMITH. The gentlewoman from Texas, Ms. Johnson, is recognized for hers.

Ms. JOHNSON. Thank you very much, Mr. Chairman, and good morning, and welcome to our distinguished panel of witnesses.

There is no denying humankind's interest in establishing whether life exists elsewhere in the universe. People have probably speculated on that possibility since time immemorial.

The question of whether there is life beyond Earth got increased attention this year following the Kepler Space Telescope's discovery of Earth-sized exoplanets in habitable zones around other stars, and Curiosity's finding of traces of water in the Martian soil.

Astrobiology, as we will hear during this hearing, is an interdisciplinary field that makes use of many fields of science to investigate the possibility of life on other worlds.

As might have been guessed, NASA has played a major role in astrobiology's development as a formal discipline. NASA's Viking missions to Mars, launched in 1976, included three biology experiments designed to look for possible signs of life. The scientific excitement generated by the Viking mission, new results from solar system exploration and astronomical research programs in the mid nineties, and advances in the fundamental biological sciences led to the establishment of the NASA Astrobiology program in 1996.

Today, NASA's Astrobiology program consists of four elements: grant programs, technological activities aimed at the development of new scientific instrumentation, technological activities aimed at the field-testing of new scientific instruments, and the NASA Astrobiology Institute.

In addition, astrobiology has become a cross-cutting theme in all of NASA's space science endeavors. For example, rather than being standalone investigations, many planetary science and astronomy missions work together in their search for life in the Universe.

Mr. Chairman, I would be remiss were I not to make note that continuing to provide adequate funding to NASA's science programs is of critical importance if we are to continue to make progress in astrobiology as well as other important scientific fields. I hope that Congress recognizes the vital contributions of ongoing and future NASA space science missions in answering whether there is life in the Universe. This hearing is an opportunity to shine light on these contributions, and I look forward to hearing from our witnesses.

I thank you, and yield back.

[The prepared statement of Ms. Johnson follows:]

PREPARED STATEMENT OF RANKING MEMBER EDDIE BERNICE JOHNSON

Good morning and welcome to our distinguished panel of witnesses.

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I hope that Congress recognizes the vital contributions of ongoing and future NASA space science missions in answering whether there is life in the Universe. This hearing is an opportunity to shine light on these contributions.

I look forward to hearing from our witnesses, and I yield back the balance of my time.

Chairman SMITH. Thank you, Ms. Johnson.

I will now introduce our witnesses. Our first witness is Dr. Mary A. Voytek. Dr. Voytek became Senior Scientist for Astrobiology in the Science Mission Directorate of NASA headquarters in 2008. Dr. Voytek came to NASA from the U.S. Geological Survey, where she headed the Microbiology and Molecular Ecology Laboratory. Dr. Voytek has served on advisory groups to the Department of the Interior, Department of Energy, the National Science Foundation and NASA including NASA's Planetary Protection Subcommittee. She received a Bachelor's in biology from Johns Hopkins University, a Master's in biological oceanography from the University of Rhode Island and a Ph.D. in biology and ocean sciences from the University of California.

Our second witness is Dr. Sara Seager. Dr. Seager is an Astrophysicist and Planetary Scientist at the Massachusetts Institute of Technology. Professor Seager chairs a current NASA Science and Technology Definition Team Study of the star shade concept for space-based direct imaging to fined and characterize other earths. Before joining MIT in 2007, Professor Seager spent four years on the senior research staff at the Carnegie Institute of Washington preceded by three years at the Institute for Advanced Study in Princeton, New Jersey. She is a 2013 MacArthur Fellow, winner of the Genius Grant; also, the 2012 recipient of the Raymond and Beverly Sackler Prize in the Physical Sciences and the 2007 recipient of the American Astronomical Society's Helen B. Warner Prize. She received her Bachelor's of Science in the Math and Physics Specialist Program from the University of Toronto. She also holds a Ph.D. in astronomy from Harvard University.

Our third witness is Dr. Steven Dick. Dr. Dick currently holds the Baruch S. Blumberg NASA Library of Congress Chair in Astrobiology at the Library of Congress. He served as the Charles A. Lindbergh Chair in Aerospace History at the National Air and Space Museum from 2011 to 2012, and as the NASA Chief Historian and Director of the NASA History Office from 2003 to 2009. Prior to that, he worked as an Astronomer and Historian of Science at the U.S. Naval Observatory in Washington, D.C. for 24 years. He obtained his B.S. in astrophysics and M.A. and Ph.D. in history and philosophy of science from Indiana University.

We welcome you all and look forward to your testimony, and Dr. Voytek, we will begin with you.

TESTIMONY OF DR. MARY VOYTEK, SENIOR SCIENTIST FOR ASTROBIOLOGY, PLANETARY SCIENCE DIVISION, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Dr. VOYTEK. Thank you. Mr. Chairman and Members of the Committee, thank you for the opportunity to appear today to discuss the topic of astrobiology.

For thousands of years, humans have looked up at the stars and wondered whether life exists beyond our home planet. This curiosity was renewed with the latest discoveries by NASA's Kepler mission totaling 3,500 new candidate planets outside our solar system. With Kepler's help, more than 800 potential worlds have now been confirmed orbiting stars other than our sun, and at least five of these are Earth-sized and orbiting within the habitable zone in each of their stars. This reminds us just how important NASA's work is to the understanding of the universe and the potential for life beyond our solar system.

A companion question that every child wonders is, where did I come from? Astrobiology seeks to answer these enduring questions. What is astrobiology? Astrobiology is the study of the origin, evolution, distribution and future of life in our universe. It addresses three basic questions that have been asked in various ways for generations: How does life begin and evolve? Does life exist elsewhere in our universe? What is the future of life here on Earth and beyond?

In striving to answer these questions, experts in astronomy, astrophysics, Earth and planetary sciences, biology, chemistry and many other relevant disciplines participate in astrobiology research to achieve a comprehensive understanding of biological, planetary and cosmic phenomena and the relationships among them.

This multidisciplinary field encompasses the search for habitable environments in our solar system as well as habitable planets outside of our solar system. Astrobiology embraces laboratory and field research into the origins and early evolution of life on Earth, the search for evidence of habitability and life on Mars and other bodies in our solar system, as well as studies of the potential for life to adapt to future challenges both here on Earth and beyond.

It is a cross-cutting theme in all of NASA's space science endeavors. It knits together research in astrophysics, Earth science, heliophysics as well as planetary sciences. The NASA Astrobiology program is guided by a community-constructed roadmap that is generated every five years. The ongoing development of this roadmap embodies the composition of diverse scientists, technologists from government, universities and private institutions. These roadmaps outline multiple pathways for research and exploration and contribute to our decisions on how our investments might be prioritized and coordinated.

NASA established its current Astrobiology program in 1996. Studies in the field of exobiology, a predecessor to astrobiology, date back to the beginning of the U.S. space program. We are proud of the results of our 50 years of cutting-edge research.

In the 20th century, astrobiology has focused on a growing number of NASA missions. As mentioned earlier, with Kepler's mission, we have been able to detect Earth-sized planets within the habitable zones around distant stars. These potentially habitable planets will expand our search for life beyond our own solar system.

Mars also continues to be an area of interest with the Curiosity rover mission currently assessing the potential habitability of that planet. In fact, results from that mission have already shown that in the past, Gale Crater could have supported microbial life.

However, since Earth is the only known example of an inhabited planet, the search for life in the cosmos begins with our understanding of life on Earth, so studying the origins and evolutions of life on Earth improves our ability to recognize and characterize life in its many imagined and yet potentially possible forms.

In 2010, astrobiologists found that a number of microbes from Earth could survive and grow in the low-pressure freezing temperatures and oxygen-starved conditions seen on Mars. Overall, astrobiologists have discovered life in numerous extreme environments on Earth such as volcanic lakes, in glaciers, sulfur springs. We have also found life in extraordinary forms ranging from bacteria that consume chemicals toxic to most life to microbes that live under high levels of gamma or ultraviolet radiation. These discoveries have taught us that life is tough, tenacious and metabolically diverse and highly capable to adapt to local environmental conditions. Knowledge gained through the astrobiology research reveals new possibilities of what else might be out there and how we might be able to find and recognize it.

An example of astrobiology technologies that have proved useful for broader application is the Chemistry and Mineralogy instrument that was developed for the NASA Curiosity rover. CheMin is a highly sensitive instrument that can identify and quantify the minerals present in the Martian rocks and is currently being used in a commercial spin-off for a variety of purposes including hazardous-material identification, mineral prospecting, artifact preservation in museums, and even detection of counterfeit pharmaceuticals in developing countries.

In conclusion, life is a central theme that unifies NASA's Science program, the science of astrobiology aims to achieve a better understanding of our own world and the life that it hosts. After 50 years, we are now in an era that can finally provide data on whether or not we are alone in the universe. This is an agenda for inspiring the next generation of explorers and stewards to sustain NASA's mission of exploration and discovery.

Again, thank you for the opportunity to testify today.

[The prepared statement of Dr. Voytek follows:]

HOLD FOR RELEASE
UNTIL PRESENTED
BY WITNESS
December 4, 2013

Statement of
Dr. Mary A. Voytek
Senior Scientist for Astrobiology
National Aeronautics and Space Administration

before the

Committee on Science, Space and Technology
U.S. House of Representatives

Mr. Chairman and Members of the Committee, thank you for the opportunity to appear today to discuss the topic of Astrobiology. For thousands of years, humans have looked up at the stars and wondered whether life exists beyond our home planet. This curiosity was renewed with the latest discovery by NASA's Kepler mission of 833 new candidate planets outside our solar system. Ten of these candidates are less than twice the size of Earth and orbit in their star's habitable zone. With Kepler's help, more than 3,500 potential worlds have now been identified orbiting stars other than our Sun, reminding us just how important NASA's work is to understand the universe and the potential for life beyond our solar system.

Even today, children wonder, where did I come from? Astrobiology seeks to answer this enduring question.

What is astrobiology?

Astrobiology is the study of the origin, evolution, distribution, and future of life in the universe. It addresses three basic questions that have been asked in various ways for generations:

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> Does life exist elsewhere in the universe?
> What is the future of life on Earth and beyond?

In striving to answer these questions, experts in astronomy and astrophysics, Earth and planetary sciences, biology and chemistry, and other relevant disciplines participate in astrobiology research to achieve a comprehensive understanding of biological, planetary, and cosmic phenomena and the relationships among them.

This multidisciplinary field encompasses the search for habitable environments in our

Solar System as well as habitable planets outside our Solar System. Astrobiology embraces the search for evidence of prebiotic chemistry and life on Mars and other bodies, laboratory and field research into the origins and early evolution of life on Earth, as well as studies of the potential for life to adapt to future challenges, both here on Earth and beyond.

Astrobiology is a community science

Astrobiology is a cross-cutting theme in all of NASA's space science endeavors, knitting together research in astrophysics, Earth science, and heliophysics as well as planetary science. As such, astrobiology is guided by a community-constructed roadmap generated every five years, most recently in 2008. The ongoing development of astrobiology roadmaps embodies the contributions of diverse scientists and technologists from government, universities, and private institutions. These roadmaps outline multiple pathways for research and exploration and indicate how they might be prioritized and coordinated.

NASA's Astrobiology Program also solicits advice from the Space Studies Board of the National Research Council (NRC). The NRC conducts studies that provide science community consensus on key questions posed by NASA and other agencies. This coordinated, collective approach to research planning has contributed to the NRC's decadal surveys for Planetary Science and for Astronomy and Astrophysics, both of which incorporate astrobiology as a key component of their programs. Within these surveys, questions encompassed by astrobiology serve as overarching themes for future planetary and astrophysics missions as a whole.

History and status of the science

NASA established its current Astrobiology Program in 1996. However, NASA studies in the field of exobiology – a predecessor to astrobiology – date back to the beginning of the U.S. space program.

Long before NASA was established, astronomers were already documenting increasingly complex organic molecules distributed throughout the universe. Similar compounds found in some meteorites and interplanetary dust particles suggest these chemicals could have been delivered to the early Earth by comets and asteroids. NASA's Viking missions to Mars in the 1970s included three biology experiments designed to look for possible signs of life.

In the 21st century, astrobiology is a focus of a growing number of NASA missions. As mentioned earlier, with NASA's Kepler mission, we have been able to detect Earth-size planets within the habitable zones around distant stars. These potentially habitable planets will expand our search for life beyond our Solar System. Mars also continues to be an area of interest, with the Mars Science Laboratory mission currently assessing the potential habitability of that planet. Recently, astrobiologists studying the Mars meteorite ALH84001 determined how and when the rock interacted with water on ancient Mars. Reconstructing the history of water on Mars is important for understanding the evolution of the atmosphere, and the potential for ancient habitats capable of supporting life. These results provided evidence that the surface of Mars was wet and clay-rich prior to 4.2 billion years ago.

However, since Earth is the only known example of an inhabited planet, the search for life in the cosmos begins with our understanding of life on Earth. Studying the origins and evolution of life on Earth improves our ability to recognize and characterize life in its many "illusory" – that is, imaginary unique -- forms.

For example, in 1977, oceanographers discovered an oasis of life around a hydrothermal vent system at the bottom of the ocean. They found communities of organisms that thrived despite high pressure, temperatures upwards of 130 degrees Celsius (water boils at 100 degrees) and the absence of sunlight. The deepest hydrothermal vents found since then were discovered along the approximately 110 kilometer long, ultra-slow spreading Mid-Cayman Rise in the Caribbean Sea. Characterization of the life at these vents has filled in a critical piece of our understanding of organisms that are fueled by chemicals rather than the Sun. Further study of these sites, which are analogs for early Earth, can help determine whether deep-sea hydrothermal vents provided an environment for the origin of life early in our planet's history.

In 2012, astrobiologists found that microbes from Earth can survive and grow in the low pressure, freezing temperatures and oxygen-starved conditions seen on Mars. Their research found that microbes from permafrost soil collected in northeastern Siberia could grow at 7 millibars of pressure. In comparison, the atmospheric pressure at the summit of Mount Everest is approximately 300 millibars, more than 40 times the global average surface pressure of Mars. In a companion study, these same scientists investigated 26 strains of bacteria commonly found on spacecraft. Incubating them under Mars-like conditions, they found that one particular bacterium, *Serratia liquefaciens*, could survive and even reproduce under these extreme conditions.

Overall, astrobiologists have discovered life in numerous extreme environments on Earth such as volcanic lakes, glaciers, and sulfur springs. We have also found life in extraordinary forms ranging from bacteria that consume chemicals toxic to most life to microbes that live under high levels of gamma or ultraviolet radiation. These discoveries have taught us that life is tough, tenacious, and metabolically diverse and highly adaptable to local environmental conditions. Knowledge gained through astrobiology research reveals new possibilities of what else might be out there and how we might be able to find and recognize it.

Benefits to Society

Astrobiology is about more than just scientific discovery. Astrobiology research and technology development has an impact on our daily lives and benefits society as a whole.

We are all familiar with the Deepwater Horizon spill of 2010 – the largest offshore spill in U.S. history. In April of that year, the United States was faced with the challenge of determining the extent of the spill, both in regard to how much oil was leaking and where the oil was moving. Astrobiology had a role in analyzing the spill. Using detectors and autonomous operation technology funded by NASA's Astrobiology Program, along with a National Science Foundation robotic submersible vehicle, scientists were able to map the underwater plume. Technology initially developed to search autonomously for environments capable of supporting life allowed the submersible to navigate along a guided path to search for the plume.

Another astrobiology technology that has proved useful for broader application is the Chemistry and Mineralogy (CheMin) instrument on NASA's Mars Science Laboratory Curiosity Rover. CheMin is a highly sensitive instrument that can identify and quantify the minerals present in Martian rocks and soil, which may provide valuable clues of where to look for biosignatures. Commercial spin-offs of CheMin technology have proved useful for a variety of purposes, including hazardous material identification, mud logging at oil drilling sites, artifact preservation in museums and even the detection of counterfeit pharmaceuticals in developing countries.

Conclusion

Life is a central theme that unifies NASA's science program. A golden age has begun for the life sciences, an age in which science and technology will benefit enormously from a fundamental understanding of the full potential of living systems. The science of astrobiology aims to achieve a better understanding of our own world and the life it hosts and also of potential habitable worlds and life beyond Earth. This is an agenda for inspiring the next generation of explorers and stewards to sustain the NASA mission of exploration and discovery.

Again, thank you for the opportunity to testify today, and I look forward to responding to any questions you may have.

Biography

Dr. Mary A. Voytek took charge of NASA's Astrobiology Program on September 15, 2008, as Senior Scientist for Astrobiology in the Science Mission Directorate at NASA HQ. Dr. Voytek came to NASA from the U.S. Geological Survey in Reston, VA, where she headed the USGS Microbiology and Molecular Ecology Laboratory. She has degrees in Biochemistry, Biology and Ocean Sciences. Dr. Voytek's primary research interest is aquatic microbial ecology and biogeochemistry. She has studied environmental controls on microbial transformations of nutrients, xenobiotics, and metals in freshwater and marine systems. She has worked in several extreme environments including Antarctica, the arctic, hypersaline lakes, deep-sea hydrothermal vents, and terrestrial deep- subsurface sites (the Chesapeake Impact Crater). She has served on several advisory groups to Department of the Interior, Department of Energy, the National Science Foundation and NASA, including the Planetary Protection Subcommittee. She has also supported NASA's Astrobiology Program serving as a NASA representative to a number of COSPAR convened studies exploring the potential for life in the universe. She has held positions in several science societies and is currently a board member of the American Geophysical Union, an organization of geophysicists, consisting of over 62,000 members from 144 countries.

Chairman SMITH. Thank you, Dr. Voytek.
And Dr. Seager.

TESTIMONY OF DR. SARA SEAGER, CLASS OF 1941 PROFESSOR OF PHYSICS AND PLANETARY SCIENCE, MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Dr. SEAGER. Mr. Chairman and Members of the Committee, we are truly at a unique time in human history. We stand on a great threshold in space exploration.

On the one side, we now finally know that small planets exist and are common, but on the other side lies the possibility to find the true Earths with signs of life. The point I want to make is, this is the first time in human history we have the technological reach to cross the great threshold. And as already explained, to infer the presence of life on an exoplanet, we will search for biosignature gases, which we define as a gas produced by life that can accumulate in an atmosphere to levels that we can detect remotely by large telescopes.

The example on Earth is oxygen, which fills our atmosphere to 20 percent by volume, but without plants and photosynthetic bacteria, we would have virtually no oxygen. So our search for biosignature gases is a search for gases that we call it "don't belong" that are produced in huge quantities that can be attributed to life.

And I would like to just say briefly that NASA-supported astrobiology has been absolutely foundational in biosignature gas research by connecting microbiologists with astronomers and geologists and planetary scientists.

The main point I want to make, a main point, is that we will not know if any exoplanet biosignature gas is produced by intelligent life, or if it is produced by simple single-cell bacteria. Right now we don't have any planets we can study for biosignature gases. The Kepler planets, while small, are too far away and too faint for any atmosphere follow-up studies.

NASA's TESS mission, led by MIT and scheduled for launch in 2017, is a two-year all-sky survey of more than half a million bright stars. Now, while TESS will not reach down to the true Earths, it will find dozens of rocky planets transiting small cool stars.

The reason we are so excited about TESS is that dozens of the TESS rocky planet atmospheres can be studied by the James Webb Space Telescope and a few of these planets are likely going to be in the star's habitable zone. So while the chance for life detection with the James Webb is very, very, very small, if life really is everywhere, we actually have a shot at it.

Now, to up our chances of finding life on an exoplanet, we need to move to a different kind of planet-finding and characterizing technique, because the TESS/James Webb combination focuses on a rare type of planet, a transiting planet that has to be aligned just so, so it goes in front of the star as seen from Earth. That is actually the easiest way to find small planets right now, but it is not the best way because we need to be able to search all of the nearby sun-like stars.

So direct imaging is the starlight-blocking technique, and it is extremely challenging because our Earth at visible wavelengths is 10 billion times fainter than our sun. Ten billion is such a huge number. This is a massive technological challenge.

But NASA is studying two different direct imaging techniques. One is the so-called internal coronagraph, where specialized optics are placed inside the telescope, but the telescope has to be incredibly specialized to be exceptionally thermomechanically stable.

The other technique is the starshade, that is, putting a giant specialized screen tens of meters in diameter and flying in formation tens of thousands of kilometers from a telescope. The starshade blocks out the starlight so only the planet light reaches the telescope. Now, the internal coronagraph is more mature, but the starshade is likely our best way to find Earths in the new future because the starshade does all the hard work. And we can have a simple telescope, relatively simple telescope, with a very high throughput.

I wanted to just briefly give you my vision for how to proceed after the James Webb Space Telescope and the TESS mission and that is we need a small space telescope mission to prove the direct imaging technique and to deliver exoplanet science. We need to demonstrate both the internal coronagraph and the starshade because we don't know which one will succeed on a larger scale and both actually may be needed. The internal coronagraph technique right now is under study for instrumentation on AFTA/WFIRST. We will be able to observe some giant planet atmospheres. The starshade and telescope system could be supported under a so-called probe-class category and could reach down on a couple of dozen stars for Earths.

Now, here is the thing. If we want to really be able to find planets with biosignature gases, we need hundreds of Earth-like planets. We need to search thousands of sunlight-stars. So for the intermediate future, we will require a large visible wavelength telescope with a large mirror exceeding 10 meters in diameter. So that is a big thing for the future but that is what it will really take if we want to up our chances of success.

So I just wanted to briefly say that the level of public interest in exoplanets has accelerated literally almost exponentially in the nearly 20 years I have been in this field. The number of people who approach me on a continual basis from high school students to MIT students to other university students to literally people all around the world to CEOs of small tech companies to retirees, these people aren't just interested in exoplanets, they want to work on exoplanets.

And so I will just close by leaving you with a vision, that this search for finding life beyond Earth is so revolutionary, it will really change the way that we see our place in the cosmos such that we believe hundreds or a thousand years from now, people will look back at us collectively as those people who first found the Earth-like worlds, and so it could be our greatest legacy. We just need to—you know, it is within our power based on our near-term decisions and investments to actually make this happen.

So Mr. Chairman and Committee, this concludes my remarks.

[The prepared statement of Dr. Seager follows:]

Statement of Sara Seager
Professor of Planetary Science, Professor of Physics, Class of 1941 Professor
Massachusetts Institute of Technology
before the
House Committee on Science, Space, and Technology
United States House of Representatives
December 4, 2013

Mr. Chairman and Members of the Committee, thank you for the opportunity to appear today to discuss astrobiology and the search for biosignatures in our Solar System and beyond.

We stand on a great threshold in the human history of space exploration. On the one side of this threshold, we know with certainty that planets orbiting stars other than the Sun exist and are common. These worlds beyond our Solar System are called exoplanets, and astronomers have found (statistically speaking) that every star in our Milky Way Galaxy has at least one planet. NASA's *Kepler* space telescope has found that approximately one in five Sun-like stars should host an *Earth-size* exoplanet in the star's habitable zone, the region around the star that is not too hot, not too cold, but just right for life. On the other side of this great threshold lies the robust identification of *Earth-like* exoplanets with habitable conditions, and with signs of life inferred by the detection of "biosignature gases" in exoplanetary atmospheres. If life is prevalent in our neighborhood of the Galaxy, it is within our resources and technological reach to be the first generation in human history to finally cross this threshold, and to learn if there is life of any kind beyond Earth.

Biosignature gases, definitions and approach

I will now turn to the scientific means by which we can cross this historic threshold, the study and future observation of exoplanet *biosignature gases*. In exoplanet research, we define biosignature gases as gases produced by life that can accumulate in a planetary atmosphere to levels detectable remotely by large telescopes. We make the assumption that life uses chemistry to capture and store energy, and that life's chemistry generates gaseous products.

Earth's most robust and abundant biosignature gas is oxygen, produced by plants and photosynthetic bacteria. Oxygen fills Earth's atmosphere to 20 percent by volume, but without photosynthetic life, our planet would be virtually anoxic, with only the faintest trace of oxygen in its air. While there are "false positive" scenarios in which atmospheric oxygen could be generated by non-living processes, such scenarios can be disentangled by observations of other gases in the atmosphere. Life on Earth generates hundreds of different gases, but usually in quantities insufficient for remote astronomical detection; some additional biosignature gases that have been considered for exoplanets include methane (CH_4), nitrous oxide (N_2O), methyl chloride (CH_3Cl), dimethylsulfide (DMS), and others. Potential astronomical observations are limited to life that generates a detectable spectroscopic signal, such that subsurface and other life that has minimal gas output will not be detectable. In addition to biosignature gases the search for water vapor

(H_2O) is key to inferring the presence of surface liquid water, a substance fundamental to all life on Earth.

I emphasize that we will not know if any biosignature gases upon an exoplanet are produced by intelligent life or by simple single-celled bacteria.

To determine the presence of biosignature gases we will need to use technically challenging, but standard astronomical telescope observing techniques to gather data on exoplanet atmospheres. We will use fundamental laws of physics and chemistry as applied to atmospheric models of the kind employed for the last few decades for solar system planets, but with adaptations for exoplanet atmospheres.

Ideally we would hope to detect oxygen (or ozone, a byproduct of oxygen), in an Earth-like exoplanet's atmosphere, but there is no guarantee that life elsewhere will generate the same gases that life on Earth does. Thus the thrust of biosignature gas research is to search for biosignature gases that "don't belong," gases that are many orders of magnitude out of equilibrium with the exoplanet atmosphere based on basic physics and chemistry. My own current research focuses on an exhaustive list of potential biosignature gases and which, based on detailed atmosphere models, can accumulate to remotely detectable levels in a wide range of conceivable exoplanet atmospheres. With these models I will interpret future data to identify gases and the likelihood that any can be attributed to life.

At present astronomers have not yet found suitable exoplanets for biosignature gas searches, because small rocky exoplanets of the type we believe are most likely to support conditions conducive to life are not observable using currently available telescopes. Future space missions will be able to study atmospheres of potentially habitable worlds. Astronomers have, however, observed atmospheres of about three dozen exoplanets with the *Hubble Space Telescope* and the *Spitzer Space Telescope*, as well as to a lesser extent with ground-based telescopes. Astronomers have been able to infer planetary temperatures and the presence of clouds, and they have identified the atmospheric presence of water, carbon monoxide, sodium, and other substances. The atmospheres studied so far are mostly limited to those of hot giant exoplanets that orbit close to their stars; giant planets in general have no surface and are too hot for life.

The progress and evolution of the field of astrobiology

The progress in the search for life beyond Earth resulting from NASA-supported astrobiology has been tremendous. The search for rocky worlds, the study of exoplanet atmospheres, and the burgeoning framework for prediction and interpretation of biosignature gases all fall under the astrobiology research umbrella. Through the start of the NASA Astrobiology Institute in 1998, NASA brought the then-obscure field of astrobiology to prominence and facilitated its interdisciplinary synthesis of astronomy, biology, chemistry, physics, and geology.

Resources, technologies, and methods

To find small exoplanets bright enough for atmosphere characterization, including the search for biosignature gases, we must find planets orbiting stars that are close to our own

Sun. Although NASA's *Kepler* space telescope has provided a critical census of exoplanets and has found a multitude of small exoplanets, the *Kepler* exoplanets are too distant from Earth for near-future follow-up studies of their atmospheres.

NASA's TESS mission (*Transiting Exoplanet Survey Satellite*), scheduled for launch in 2017, will survey nearby stars for transiting exoplanets. Transiting exoplanets are those that pass in front of their parent star as seen from the telescope, and this is the same technique NASA's *Kepler* mission used to discover more than 3,500 exoplanet candidates. TESS is a NASA Explorer-class mission (230 million dollars cost cap, exclusive of launch costs) led by MIT. TESS will carry four identical specialized wide-field CCD cameras, each covering 24 degrees x 24 degrees on the sky with a 100 mm aperture. In a two-year all-sky survey of the solar neighborhood, TESS will cover 400 times as much sky as did *Kepler*. In the process, TESS will examine more than a half million bright, nearby stars, and will likely find thousands of exoplanets with orbital periods (i.e. "years") up to about 50 days. TESS will not be able to detect true Earth analogs (that is, Earth-size exoplanets in 365-day orbits about Sun-like stars), but it will be capable of finding Earth-size and super Earth-size exoplanets (up to 1.75 times Earth's size) transiting M stars, stars which are significantly smaller, cooler, and more common than our Sun. TESS is projected to find hundreds of super Earths with a handful of those in an M star's habitable zone. Extensive follow-up observations by ground-based observatories in the United States and internationally will then be used to measure the planet mass to confirm the exoplanets as being rocky.

NASA's *James Webb Space Telescope* (JWST), scheduled to launch in 2018, will be capable of studying the atmospheres of a subset of the TESS rocky exoplanets in visible, near infrared, and infrared light. The technique JWST will use is called transit spectroscopy. As a transiting exoplanet passes in front of its host star, we can observe the exoplanet's atmosphere as it is backlit by the star. 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. We anticipate TESS will find dozens of super Earths suitable for atmosphere observations by JWST, including several that could potentially be habitable. The chance for life detection with the TESS-JWST combination—albeit small—is a possibility if life turns out to be ubiquitous.

The exoplanet discovery and atmospheric characterization techniques of the TESS-JWST combination are powerful, but are very limited to the rare set of exoplanets that are fortuitously aligned to transit their host stars. A different kind of exoplanet finding and characterization technique is required to increase the chances of finding an exoplanet with habitable conditions and signs of life. Simply put, we need to take pictures of potentially habitable exoplanets. Astronomers call this direct imaging. To maximize our chances for finding life beyond the Solar System, we must develop the capability to directly image exoplanets around as many nearby stars as possible.

Any Earth-like exoplanets within dozens of light-years are not fainter than the faintest galaxies ever observed by the *Hubble Space Telescope,* but, first, to detect biosignature gases we have to divide the light into individual wavelengths to detect spectra hence we will ultimately need telescopes larger than *Hubble*, and second and even more challenging is that these exoplanets are adjacent to a parent star that is up to 10 billion times brighter than the planet itself. The challenge of direct imaging of an Earth analog 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.

Two different direct imaging techniques are currently under development by NASA that in the future could enable direct imaging of Earth analogs. One is the internal coronagraph, 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. NASA has supported university and NASA center-based studies of a variety of different coronagraph architectures, including deformable mirrors for ultra precise wavefront control, and facilities including the High Contrast Imaging Testbed (HCIT) at the Jet Propulsion Laboratory. NASA is investigating the addition of an internal coronagraph instrument to the AFTA-WFIRST[1] mission, and while such an instrument would not reach down to observe small exoplanets, it would be able to study atmospheres of giant exoplanets.

The second NASA-supported technique for direct imaging of Earths is a starshade and telescope system. A starshade (also called an external occulter) is a spacecraft with a carefully shaped screen 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 and telescope system may be the best near-term step for discovering and characterizing nearby Earth analogs; because the starlight blocking is done by the starshade outside of the telescope itself, the telescope system throughput can be made very high and a relatively simple and small commercially available space telescope can be used. Starshade technology development draws on industrial heritage of large space-based deployable radio antennas. So far, technology milestones include subscale vacuum chamber and environmental 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.

[1]Astrophysics Focused Telescope Asset; Wide-Field Infrared Survey Telescope

NASA is currently supporting science and technology definition teams (STDTs) for both the internal coronagraph and the starshade for Probe-Class mission concepts (cost cap under 1 billion dollars) and these studies will be completed by January 2015. I chair the starshade STDT.

My personal vision for the path to find small planets and search for biosignature gases is as follows.

1. The TESS-JWST combination is our first step to discover and characterize potentially habitable exoplanets transiting the nearest small stars.

2. Direct imaging of exoplanets via a small-telescope space mission to both prove the technology and deliver breakthrough exoplanet science, at the same time laying the groundwork for a larger-scale system. Both the internal coronagraph and the starshade must be supported until we are confident of which is the best approach; both may be needed. The internal coronagraph technique is under study for instrumentation on AFTA and will be able to observe atmospheres of known giant exoplanets. The starshade has two options for near-term implementation. One option is a starshade built separately but flown in combination with AFTA; in this case AFTA must be launched to an orbit away from Earth orbit (to minimize pollution from Earth's reflected light and to enable large-separation formation flying). The second option is a complete mission of the starshade and telescope system, under the Probe-class category. The latter option could reach a few dozen stars to search for Earths. If needed, to reduce the overall cost the United States could develop and build the starshade while international partners could supply the telescope and its spacecraft and launch vehicle.

3. Direct imaging for exoplanet detection and atmospheric search for biosignature gases via a large space-based telescope. To be certain of finding a large enough pool of exoplanets to search for biosignature gases, we require the ability to directly image exoplanets orbiting 1,000 or 10,000 of the nearest Sun-like stars. This will require a next-generation space telescope beyond JWST, a visible wavelength telescope with a large diameter likely exceeding 10 meters. Studies are ongoing within the astronomy community and NASA to outline the mission concept and technology investment required.

The practicalities and budget realities may not permit the detection of biosignature gases in the near future. However, the first step towards the robust identification of potentially habitable worlds will be made with the TESS-JWST combination.

The second step in the above vision is within reach if we consider that the astrophysics funding wedge currently supporting the JWST can and should be repurposed in the future for exoplanet-focused space-based direct imaging missions.

The third step can be supported in the short term by continued technology development for the internal coronagraph, the starshade, and large space-based mirrors and telescopes. The development of large space-based mirrors has additional applications in many areas of astronomy and defense.

The value of astrobiology

Astrobiology and the search for life beyond the Solar System contributes directly to one of NASA's main science questions, " Are we alone?" The quest for understanding of the origin and evolution of habitable worlds and life beyond the Solar System is specified in NASA documents including the 2010 National Space Policy, 2011 NASA Strategic Plan, 2010 SMD Strategic Plan, 2012 Astrophysics Strategic Plan, and the National Academy of Sciences Astrophysics Decadal Survey, the 2010 New Worlds New Horizons.

NASA missions inspire the next generation of explorers. My experience with science and engineering students at MIT and elsewhere is that they 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. Even though most students may not end up as exoplanet researchers or planetary science mission engineers, with their advanced technical skills and abilities they will go on to work in and greatly contribute to many other research areas, including aerospace technology development, remote sensing, and data analysis. By investing in university-supported astrobiology space-mission related research we can continue to train a workforce for technology leadership of the future. 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.

The lure of astrobiology is not limited to undergraduate and graduate students. Exoplanets and specifically the promise of finding other Earths offer major opportunities for deep public engagement. Exoplanet discoveries are constantly in the news. People of all walks of life are inspired by astrobiology, and so many seek to be involved, either students via STEM education or other individuals through grassroots internet-based "citizen science" projects. People all around the world, at all levels, from individuals to organizations, are awakening to the realization that finding life elsewhere in our Galaxy would forever change how we see ourselves and our place in the cosmos.

In July 2010 I became a citizen of the United States of America, motivated by our nation's uniqueness in its combination of technological forte, allocated resources for space missions, and ambitious spirit. It is within the power of our influence to cross the great historical threshold and be the first generation in human history to map the nearby exoplanetary systems and find signs of life on other Earth-like worlds. As a country, this achievement may prove to be our greatest legacy. As a species, it may be the beginning of our boldest adventure. I imagine that hundreds or a thousand years from now, our descendants will find a way to travel to these nearby star systems, and embarking on their interstellar journey will look back upon us here in the 21st century as those who first found the Earth-like worlds.

Mr. Chairman and Committee this concludes my remarks. Thank you for your attention and your continued support of this revolutionary area of research – the search for life beyond our Solar System.

Professor Sara Seager, Biography

Sara Seager is an astrophysicist and planetary scientist at the Massachusetts Institute of Technology. Her science research focuses on theory, computation, and data analysis of exoplanets. Her research has introduced many new ideas to the field of exoplanet characterization, including work that led to the first detection of an exoplanet atmosphere. Professor Seager's space instrumentation group is focusing on "ExoplanetSat", a "3U CubeSat" nanosatellite capable of high-precision pointing, with the science goal of detecting small transiting exoplanets orbiting bright, sun-like stars. The prototype is intended to be the first of a planned fleet of nanosatellites, aimed to demonstrate the graduated growth of a constellation as a new paradigm for space science missions. In addition to being the PI of ExoplanetSat, Professor Seager is a co-I on the MIT-led TESS, a NASA Explorer Mission to be launched in 2017, an all-sky survey for transiting exoplanets including a focus on finding rocky planets transiting small stars. Professor Seager chairs a current NASA Science and Technology Definition Team study of the starshade concept for space-based direct imaging to find and characterize other Earths.

Before joining MIT in 2007, Professor Seager spent four years on the senior research staff at the Carnegie Institution of Washington preceded by three years at the Institute for Advanced Study in Princeton, NJ. Her PhD is from Harvard University. Professor Seager is on the advisory board of the asteroid mining company Planetary Resources. Professor Seager is a 2013 MacArthur Fellow, the 2012 recipient of the Raymond and Beverly Sackler Prize in the Physical Sciences, and the 2007 recipient of the American Astronomical Society's Helen B. Warner Prize. She has been recognized broadly in the media, most recently in Time Magazine's 25 Most Influential in Space in 2012.

Chairman SMITH. Thank you, Dr. Seager.
Dr. Dick.

TESTIMONY OF DR. STEVEN DICK, BARUCH S. BLUMBERG CHAIR OF ASTROBIOLOGY, JOHN W. KLUGE CENTER, LIBRARY OF CONGRESS

Dr. DICK. Chairman Smith, Ranking Member Johnson and Members of the Committee, thank you for the opportunity to testify today on the subject of the past and future of astrobiology. I do so not as a practitioner in the field but as an historian of science who for four decades has documented the debate over life beyond Earth. In that role, I can say that this is a subject rich in history and promise and one that fascinates the American public.

During my time as NASA Chief Historian, everywhere I went people wanted to know about life on other worlds, and they still do. Astrobiology raises fundamental questions and evokes a sense of awe and wonder as we realize perhaps there is something new under the sun and other the suns of other worlds.

The key discoveries in astrobiology over the last decade have evoked that sense of awe and wonder. High on the list must be the discovery of planets beyond our solar system, those so-called exoplanets are the very first goal of the NASA Astrobiology Roadmap.

Ground-based telescopes as well as the Hubble and Spitzer telescopes have all contributed to these discoveries, and NASA's Kepler spacecraft has opened the floodgates. By the end of 2013, almost a thousand planets have been confirmed. Thousands more are awaiting confirmation. Smaller and smaller planets are being detected including Super Earths and Earth-sized planets.

A second highlight is the continued search for life in our solar system—goal 2 of the roadmap. A fleet of spacecraft over the last decade has demonstrated that Mars had enough liquid water in the past to be habitable for life. Spacecraft have probed the icy moons of the outer solar system including the Jovian moon Europa and the Saturnian moon Enceladus. The still-ongoing Cassini/Huygens mission has found on the Saturnian moon Titan an atmosphere believed to be rich in prebiotic organic compounds and lakes of methane on the surface of that satellite. And just a few months ago, Cassini captured an image of Earth, a pale blue dot against the darkness of space.

Another of the highlights over the last decade has been to demonstrate further the tenacity of life in extreme environments—goal 5 of the Astrobiology Roadmap. Life has been found in hydrothermal vents deep below the ocean, kilometers below the ground, way above the boiling point of water, way below its freezing point. The point is that life is more tenacious than once thought and so may arise on planets under conditions once thought unfavorable. Genomic analysis of these microorganisms continues to shed light on how they function.

Among the critical issues in the search for life in the solar system during the next decade will be a continued research program on past and present life on Mars, employing spacecraft such as MAVEN, which was just launched two weeks ago, as well as continued field and laboratory research on the origins, limits and future of life on Earth and other planets. Beyond the solar system, the challenge now is to classify and characterize newly discovered planets as well as the search for even smaller ones. Over the next decades, spacecraft such as TESS will search for rocky planets and stars, and the James Webb Space Telescope will further characterize those planets and their potential for life by searching for biosignatures in their atmospheres. This is goal 7 of the roadmap.

I would like to say also that in my view, renewing the search for radio and other artificial biosignatures as part of the search for extraterrestrial intelligence, SETI, would enhance NASA's Astrobiology program and repair the artificial programmatic divorce that now exists between the search for microbial and intelligent life. No biosignature would be more important than a radio signal from another civilization on one of those newly discovered planets, perhaps, especially if they have something to say.

In concluding, I would be remiss if I failed to mention that among the issues and challenges for the next decade are goals related to astrobiology and society. Indeed, the Astrobiology Roadmap recognizes as one of its four implementation principles a broad societal interest in its endeavors. Astrobiology raises profound questions with respect to the impact on society. What will be the effect on our world views, our philosophies and religions, if we discover microbial or intelligent life beyond the Earth? Are there useful analogies that will help us to evaluate societal impact?

History indicates that the discovery, or the failure to discover extraterrestrial life, is likely to be an extended affair as in the debates over the Viking spacecraft results and the ALH84001 Mars rock controversy. These are the kinds of societal aspects of astrobiology that I am now studying as part of my time at the Library of Congress. Others are also studying these societal impact questions, especially in the last five years since the NASA Astrobiology Institute has supported a roadmap and a focus group on astrobiology and society.

Finally, let me say that in my view, astrobiology embodies the most important ideals of discovery, exploration and inspiring our explorers for the next generation. No better hook exists in my experience to get students interested in science than the tantalizing and interdisciplinary questions of astrobiology. I always like to quote Nobelist Baruch Blumberg, the first Director of the NASA Astrobiology Institute and the inspiration behind the Blumberg NASA Library of Congress Chair that I hold now at the Library's Kluge Center, which brings together scholars and policymakers. Astrobiology, Dr. Blumberg said, is in the best tradition of our species and in the best American tradition dating back to Lewis and Clark, to ask great questions, to explore our world and other worlds, to infuse our culture with new ideas, and to evoke that sense of awe and wonder as we discover the true place of our pale blue dot in the universe.

Thank you.

[The prepared statement of Dr. Dick follows:]

Testimony of
Dr. Steven J. Dick
Baruch S. Blumberg NASA/Library of Congress Chair in Astrobiology

before the

Committee on Science, Space, and Technology
U.S. House of Representatives
December 4, 2013

Chairman Smith, Ranking Member Johnson, and members of the Committee, thank you for the opportunity to testify today on the subject of the past and future of astrobiology. I do so not as a practitioner in the field, but as a historian of science who for four decades has documented the debate over life beyond Earth, including in the context of NASA (Steven J. Dick and James E. Strick, *The Living Universe: NASA and the Development of Astrobiology* (Rutgers University Press, 2004). In that role I can say this is a subject rich in history and promise, and one that fascinates the American public. During my time as NASA Chief Historian, everywhere I went people of all ages wanted to know about life on other worlds. Astrobiology raises fundamental questions and evokes a sense of awe and wonder as we realize perhaps there *is* something new under our Sun, and the Suns of other worlds.

Key Discoveries in Astrobiology Over the Last Decade

The key discoveries in astrobiology over the last decade have evoked that sense of awe and wonder. High on the list must be must be the discovery of planets beyond our solar system, those so-called exoplanets that are the very first goal of the NASA Astrobiology Roadmap. Ground-based telescopes, as well as the Hubble and Spitzer space telescopes, have all contributed to these discoveries. But NASA's Kepler spacecraft has opened the floodgates. Twenty years ago no planets were known around Sun-like stars. As of the end of 2013 more than 1000 planets have been confirmed, and thousands more are awaiting confirmation. Smaller and smaller planets are being detected, including Super Earths and Earth-sized planets. Kepler-37b is only slightly larger than our Moon, one of at least three planets in its system. Kepler-62e and Kepler-62f are only about 50% larger than our Earth, and orbit in the habitable zone of their system. Scientists at the Kepler Science Conference last month reported that smaller planets are now being discovered at the most rapid rate, that most stars in our galaxy have at least one planet, and that one in five Sun-like stars are likely to have Earth-sized planets orbiting in their habitable zone.

A second highlight is the continued search for life in our solar system – Goal 2 of the Roadmap. Past spacecraft, including the Mars Global Surveyor, Mars Odyssey, the Mars Exploration Rovers (Spirit and Opportunity), the Mars Reconnaissance Orbiter, as well the Curiosity Rover, have demonstrated that Mars had enough liquid water in the past to be hospitable for life. In 2008 the Phoenix Lander detected the presence of shallow subsurface water, and only a few months ago researchers reported that Curiosity's first sample of Martian soil was composed of about 2 percent water. The Martian polar caps harbor large amounts of frozen water and carbon dioxide. Meanwhile, spacecraft have probed the icy moons of the outer solar system, including the Jovian moon Europa and the Saturnian satellite Enceladus. Europa almost certainly has an ocean under its icy crust, and Enceladus outdoes its Jovian counterpart by spouting jets of water vapor from beneath its icy surface. The still-ongoing Cassini/Huygens mission has found an atmosphere, believed to be rich in prebiotic organic compounds on the Saturnian moon Titan, and in 2006 discovered lakes of methane on the satellite. In a broader activity, just a few months ago Cassini captured an image of Earth, a pale blue dot against the darkness of space, as seen through the rings of Saturn.

Another of the highlights over the last decade has been to demonstrate further the tenacity of life in extreme environments – Goal 5 of the Astrobiology Roadmap. Life has been found in hydrothermal vents at high temperatures and pressures deep below the ocean; it has been found three kilometers below the ground employing radioactivity rather than photosynthesis for its metabolic processes; it has been found way above the boiling point of water in the brilliant hot spring of Yellowstone and way below its freezing point in the deserts of Antarctica, under conditions of extreme radiation, salinity, acidity and so on. The point is that life is much more tenacious than once thought, and so may arise on planets under conditions once thought unfavorable. Genomic analysis of these microorganisms continues to shed light on how they function.

Recently scientists have found evidence of microbial life in 3.48 billion year-old rocks in Australia, the oldest biosignatures yet found on Earth. These findings also feed into the origins of life debate, and if true, indicate that life arose relatively quickly after the late heavy bombardment of the Earth that ended about 3.8 billion years ago. These findings are likely to remain controversial over the next decade, similar to the Braiser-Schopf controversy that erupted in 2002 over the 3.45 billion year old Apex chert microfossils. Such controversy is an integral part of the scientific enterprise.

These are only some of the highlights of the numerous studies undertaken under the banner of astrobiology. More details are found in the Annual Reports of the NASA Astrobiology Institute (https://astrobiology.nasa.gov/nai/reports/annual-reports/). Uniting all these studies is the concept of cosmic evolution – the 13.8 billion year unfolding of the universe, resulting in galaxies, stars and planets – and in at least one case, life. Cosmic evolution provides the context for astrobiology, which among other things seeks to follow the evolution of organic compounds from the interstellar medium through protoplanetary disks to habitable planets, possibly including delivery by comets, and to understand how these organics gave rise to life on Earth.

Critical Issues and Challenges for Next Decade

The challenge now from an observational point of view is to classify and characterize the newly discovered planets, as well as to search for even smaller ones, especially those in the habitable zones of their parent stars. Over the next decade spacecraft such as the Transiting Exoplanet Survey Satellite (TESS) will search for rocky planets around stars, and the James Webb Space Telescope will further characterize these planets and their potential for life by searching for biosignatures in their atmospheres, Goal 7 of the Astrobiology Roadmap. Already in February of this year detection of carbon monoxide and water absorption lines were reported in a massive planet circling the star HR 8799, revealing the planet's chemical composition, atmospheric structure, and surface gravity (Konopacky et al., Science, 339, 1398). Ever more detailed spectra of ever more planetary atmospheres will surely be a major priority over the next decade. At the same time theoretical studies of the formation of circumstellar disks and planets will shed light on how other solar systems came to exist, illuminating their structure and how unique our solar system is. Numerous theoretical challenges exist, not least to explain how so many planets came to orbit so close to their parent stars.

Among the critical issues in the search for life will be a continued research program on past or present life on Mars, employing spacecraft such as MAVEN just launched two weeks ago. Mars Odyssey, Mars Express, the Mars Reconnaissance Orbiter, the Opportunity Rover, and the Mars Science Laboratory (Curiosity) will continue to return data as long as batteries and funding last. Meanwhile, Mars remains a planet of mystery in many ways. Claims of methane of possible biogenic origin have been made based on observations from Earth and from Mars orbit, but the Curiosity rover, using its laser spectrometer, has not detected any. Mars clearly had surface water in the past, as evidenced by channel and outflow features. Where and when did all the water go? Why did the climate of Mars change so remarkably? Results from the Phoenix lander in 2008 in the form of perchlorates on the Martian surface – a toxic compound of chlorine and oxygen – have even reopened the interpretation of the results of the biological experiments aboard the Viking landers from the late 1970s. These questions, and other, will likely be resolved over the next decade.

Research on the origins and limits of life on Earth will continue with the goal of elaborating a "universal biology" that applies not only to Earth but also to other planets. Today the debate is at the level of the molecular assembly of life, determining the geochemical steps that led to the origin of life on Earth. A major task will be to identify the origin of the first replicating molecules, which some researchers believe to be found in the "RNA world," in which RNA is able to both store information and catalyze reactions. In this scenario RNA was the predecessor to current life, based on DNA. Major gaps remain in this scenario, however, and the next decade could determine whether this, or another theory, comes to the fore. Origins of life work also incorporates the work of the late Carl Woese, who showed that single-celled organisms on Earth ("prokaryotes") actually consist of two distinct domains, archaea and bacteria, and that the archaea are actually closer to the third domain of life, eukarya (including plants and animals).

Work on biosignatures will continue in the atmospheres of other planets, but also in rocks and microbial ecosystems with environments analogous to early Earth. The results from studies of ancient biosignatures on Earth can be used to search for biomarkers on other planets.

One of the most appealing characteristics of astrobiology is that the discipline forces us to ask questions that put in perspective our place in the universe: What are life, consciousness, and intelligence in a universal context, and what are the metaphysical assumptions that underlie our understanding of these concepts? Is there a general theory of living systems, a universal biology as there is a universal physics? What are culture and civilization? What is our place in the 13.8 billion-year unfolding of cosmic evolution? Some of these questions bearing on consciousness and intelligence are beyond the scope of the current NASA astrobiology program, but they are nevertheless an important part of the search for life in the universe. Almost exactly twenty years ago, in the same session that saw the demise of the Superconducting Super Collider, the 103rd Congress terminated the NASA Search for Extraterrestrial Intelligence (SETI) program. In addition to a renewed search with the latest technology, the reinstatement of funding for SETI would allow a systematic examination of these intriguing questions. It would also repair the artificial programmatic divorce between the search for microbial and intelligent life, which, despite engaging different scientific communities, are part of the same research problem. And I believe SETI would be supported by the public, which as always is interested in life beyond Earth, whether microbial or intelligent.

The work described here is carried out by the 15 teams of the NASA Astrobiology Institute (NAI), plus individual grantees in NASA's Exobiology and Evolutionary Biology grant programs. In 2012 alone, NAI teams issued 172 project reports and 849 publications. These teams are guided by the NASA Astrobiology Roadmap, initially developed in 1998, and updated in 2003 and 2008. The 2008 Roadmap is now being updated as part of the 2014 Astrobiology Strategic Plan. The consolidation and expansion of astrobiology's goals over the last two decades demonstrate how the field is rapidly changing based on new ideas and new evidence. (see http://astrobiology.nasa.gov/roadmap/ for all three versions of the Roadmap).

Other institutions in the United States and around the world are also involved in such research. Astrobiology continues to become an ever-more robust discipline, defying past labels as a "science without a subject." That label is a misrepresentation of science. Every science is looking for its subject until it finds it, as in the case of planetary systems, the Higgs boson, and gravitational waves. From an epistemological point of view, the methods of astrobiology are as empirical as in any historical science such as astronomy or geology, though it is true that astrobiological observations and experiments are often especially difficult.

Astrobiology and Society

I would be remiss if I did not mention that among the issues and challenges for the next decade are those related to astrobiology and society. Indeed the Astrobiology Roadmap recognizes as one of its four implementation principles "a broad societal interest in its endeavors." Just as the American Association for the Advancement of Science and the National Science Foundation recognize the importance of studies of Science and Society, and just as some university programs across the country study the interactions of Biology and Society, including the ethical, legal and social implications of the Human Genome Project, so astrobiology raises profound questions with respect to the impact on society.

What will be the effect on our worldviews, philosophies and religions if we discover microbial or intelligent life beyond Earth? Are there useful analogies, such as the changes in worldview in the wake of the Copernican and Darwinian revolutions? A study of the nature of discovery indicates that the discovery of life beyond Earth is likely to be spread over an extended period of time, as in the debates over the Viking spacecraft results, and the ALH84001 Mars rock controversy. A second quite different critical issue in the domain of Astrobiology and Society may be formulated as follows: What are the ethical issues in pursuing the search for extraterrestrial life? How do we balance planetary protection and stewardship with the human exploration imperative, of which astrobiology is a significant part? NASA has for decades had a Planetary Protection program to address these issues, to ensure protection of "all of the planets all of the time." The gravity of the issues can hardly be over-emphasized, not only because of the real prospect of forward contamination of planets, but also because a single "Andromeda Strain" scenario would be enough to jeopardize the terrestrial biosphere.

These are the kinds of humanistic aspects of astrobiology I am studying as part of my time at the Library of Congress, where, in a related event a few weeks ago, we celebrated the opening of the papers of Carl Sagan, known worldwide for his work in astrobiology. Others are also studying these societal impact questions, especially since 2011 when the NASA Astrobiology Institute supported a Roadmap and a focus group on Astrobiology and Society (Margaret Race, Kathryn Denning et al, "Astrobiology and Society: Building an Interdisciplinary Research Community," *Astrobiology*, 12 (2012), 958-965.

Finally let me say that in my view astrobiology embodies the most important ideals of discovery and exploration. I like to quote Nobelist Baruch S. Blumberg – the first Director of the NASA Astrobiology Institute and the inspiration behind the Blumberg NASA/Library of Congress Chair in Astrobiology that I hold at the Library's Kluge Center, which brings together scholars and policymakers. Astrobiology, Dr. Blumberg said, counters the usual academic trends by drawing in numerous disciplines rather than compartmentalizing knowledge and increasing specialization. Moreover, it is in the best tradition of our species, and in the best American tradition dating back to Lewis and Clark to ask great questions, to explore our world and other worlds, to infuse our culture with new ideas, to be changed for the better because of that exploration, and to evoke that sense of awe and wonder as we discover the true place in the universe of our pale blue dot.

Steven J. Dick

Steven J. Dick currently holds the Baruch S. Blumberg NASA/Library of Congress Chair in Astrobiology at the Kluge Center of the Library of Congress. He served as the Charles A. Lindbergh Chair in Aerospace History at the National Air and Space Museum from 2011-2012, and as the NASA Chief Historian and Director of the NASA History Office from 2003-2009. Prior to that he worked as an astronomer and historian of science at the U. S. Naval Observatory in Washington, D.C. for 24 years, including three years on a mountaintop in New Zealand. He obtained his B.S. in astrophysics (1971), and MA and PhD (1977) in history and philosophy of science from Indiana University.

Among his books are *Plurality of Worlds: The Origins of the Extraterrestrial Life Debate from Democritus to Kant* (Cambridge University Press, 1982) (translated into French), *The Biological Universe: The Twentieth Century Extraterrestrial Life Debate and the Limits of Science* (Cambridge University Press, 1996), and *Life on Other Worlds* (Cambridge University Press, 1998), the latter translated into Chinese, Italian, Czech, Greek and Polish. He has also authored (with James Strick) *The Living Universe: NASA and the Development of Astrobiology* (2004), and a comprehensive history of the U. S. Naval Observatory, *Sky and Ocean Joined: The U. S. Naval Observatory, 1830-2000* (Cambridge University Press, 2003). The latter received the Pendleton Prize of the Society for History in the Federal Government. He is also editor of *Many Worlds: The New Universe, Extraterrestrial Life and the Theological Implications* (2000), and (with Keith Cowing) *Risk and Exploration: Earth, Sea and Stars* (NASA SP-2005-4701 (Washington, D.C., 2005). His latest works are edited volumes in the NASA History series; a full list is at http://www.stevenjdick.com/Steven_Dicks_Website/Welcome.html. His book *Discovery and Classification in Astronomy: Controversy and Consensus* was published by Cambridge University Press in 2013.

Dr. Dick is the recipient of the NASA Exceptional Service Medal, the Navy Meritorious Civilian Service Medal, the NASA Group Achievement Award for his role in NASA's multidisciplinary program in astrobiology, the NASA Group Achievement Award for the book *America in Space*, and the 2006 LeRoy E. Doggett Prize for Historical Astronomy of the American Astronomical Society. In 2012 he was elected a Fellow of the American Association for the Advancement of Science (AAAS). He has served as Chairman of the Historical Astronomy Division of the American Astronomical Society, as President of the History of Astronomy Commission of the International Astronomical Union, and as President of the Philosophical Society of Washington. He is a member of the American Astronomical Society, the International Astronomical Union, and a corresponding member of the International Academy of Astronautics. In 2009 the International Astronomical Union designated minor planet 6544 stevendick in his honor.

Chairman SMITH. Thank you, Dr. Dick.

Let me address my first question to Dr. Voytek and Dr. Dick. First of all, this is an exciting subject, even an inspirational one. It is also, I think worth noting that space exploration, including the kinds of exploration we are talking about today, attracts bipartisan interest and bipartisan support. So, that is nice from the point of view of Members of Congress, and also the subject has literally caught the public's imagination, and that is something to build on and something to encourage as well.

But Dr. Voytek and Dr. Dick, you both mentioned the Astrobiology Roadmap. The last official roadmap was 2008. Supposedly there is one every five years. I understand the 2013 is actually coming out in 2014, May, June or thereabouts. But my question is this: when it comes to astrobiology, what should be our goals today if you could write the roadmap? Obviously it has changed a lot in the last five years but what should be our astrobiology goals today? Dr. Voytek?

Dr. VOYTEK. So the current roadmap is being developed to align—well, to——

Chairman SMITH. What would be your goals?

Dr. VOYTEK. My goals would be to better enable the search for life outside of Earth, which includes really pushing our knowledge base about what is possible for life in general. So to extend our research on extreme environments and push it to the limit in terms of what kinds of conditions to better establish habitability off the Earth.

Chairman SMITH. Right.

Dr. VOYTEK. And I believe that we also need to push hard in the area of synthetic biology to understand the basic building blocks of life to enable a better search strategy for the potential types of life. I anticipate that the first life we find is likely to be a microbial, relatively simple life form, and that it will be essential to know as life did on this planet, it made itself from what was around it. It is likely it will do the same on other planets, and so we need to be mindful of what other possibilities there are.

Chairman SMITH. Thank you.

Dr. Dick?

Dr. DICK. Well, aside from what has already been said, I would like to see a voyage to Europa to find out what is under the——

Chairman SMITH. I would too.

Dr. DICK. —thick ice, what is swimming around down there perhaps, or also out to Saturn with Enceladus and to find out more about those water spouts that are shooting out of Enceladus. There might be biosignatures there.

Chairman SMITH. I think Europa is already on the list but we will have to expedite that.

Dr. DICK. Right.

Chairman SMITH. Okay.

Dr. DICK. Also, I would say, as I mentioned, that I think it would be great to repair this divorce between microbial—the search for microbial intelligent life by including a more robust program on SETI.

Chairman SMITH. Okay. Good. Thank you, Dr. Dick.

Dr. Seager, I like your word "revolutionary" when it comes to the possible discovery of microbes or other interesting forms of life elsewhere on other planets. What I wanted to ask you, and you went into some detail as to how we might be able to detect these biosignatures, but could you give us a hopeful timeline when might this occur? I know that there are certain dates for the launches of these various telescopes, but some people think we might actually achieve some breakthroughs with the devices and the equipment we have today, but I just want you to speculate. Do you think in what time frame might we expect to find some evidence of, say, microbial life elsewhere in the universe?

Dr. SEAGER. I always like to start by saying scientists never like to speculate. We always like facts.

Chairman SMITH. But you always do.

Dr. SEAGER. But we always do. Correct.

So let us say our input is that every—just for argument's sake, if every star has an Earth and every Earth has life, then we will find—we have a great chance of finding the first signs of it with the TESS/James Webb Space Telescope combination. It is likely that it is not that common. We see evidence already that not every star has an Earth-size planet in the habitable zones, but many do. In that case, we need to go to a direct imaging mission in space, and there is no plan on the books for that. We have lots of studies going on. If that one could be implemented, when it is launched it would take a few years. In that case, we also have to be lucky. If it is correct that one in five stars like the sun now has an Earth, and every one of those has life, then we would be able to find signs of life with that relatively small space telescope mission.

My best guess, if you wanted the honest, very conservative answer, if I have to——

Chairman SMITH. Yes.

Dr. SEAGER. —come back and be the one who has to hold the responsibility for this, I would say we need that next-generation telescope beyond the James Webb, the big telescope in space. So we need to invest in technology now so this can actually happen at some point. But once that one goes up, it would just be a matter of a few years to survey enough stars for planets and find them.

So I have given you the most optimistic case, somewhat unrealistic, that the James Webb finds it. The least optimistic case, we need to find out how to put a large mirror in space to search enough to have a high enough chance.

Chairman SMITH. Okay. Most optimistic then next five to 10 years?

Dr. SEAGER. Yes, the most optimistic is within a decade.

Chairman SMITH. Okay.

Dr. SEAGER. But I don't want to leave you with just being optimistic because I don't—you know, we really do need to invest in the future.

Chairman SMITH. Right. I understand that. Thank you, Dr. Seager.

My last question is for you all starting with Dr. Voytek. What can we do to expedite the process? And that is a pretty general question. Some of the answers have probably been given, the development of these various telescope, tests and so forth, but what can we as Members of Congress do to expedite the process? I have a hunch probably the answer is going to be funding, but so be it.

Dr. VOYTEK. Well, I was going to say continued support. Congress and the Administration has provided excellent support to the Planetary Sciences Division and Astrophysics and Science Mission Directorate in general, and so we need your continued support. I know that funding is tough but that is the best thing you can do.

Chairman SMITH. Okay. If we make it a priority, we can achieve that five to ten year time frame perhaps.

Dr. Seager?

Dr. SEAGER. I would say that keeping our outreach abilities in the university system with the experts who are actually working on the field is so important. I think people don't quite understand how often—you know, you think outreach happens maybe at the museum or elsewhere, but as individuals, we actually do a huge amount of this, and it is sort of inspiring the next generation so we make sure we have that pool of people to keep us not only at the forefront of space technology but in biology and keeping this interest moving along. I think that is the best investment we have.

Chairman SMITH. Great. Okay.

Dr. Dick?

Dr. DICK. Aside from funding, I think just the idea that we know that Congress is behind the program including, for example, the SETI program. I think that we are still seeing the repercussions from 20 years ago when that program was canceled, and NASA is not forbidden from funding that but they realize that Congress has sort of discouraged that 20 years ago.

Chairman SMITH. I think there is more interest today and more possibilities today with the discovery of all these exoplanets. Thank you, Dr. Dick.

My time is way over. The gentlewoman from Texas, the Ranking Member, is recognized for her questions.

Ms. JOHNSON. Thank you very much.

I guess this question is for all of you. To what extent are the interagency and international collaborations important to the astrobiology and what, if anything, is needed to facilitate that collaboration to maximize the progress and findings?

Dr. VOYTEK. I will start with that. The Astrobiology program when we established the Institute, part of its charter was to explore means to enhance collaboration amongst all nations that are interested in the questions that are addressed by astrobiology, and we have been very successful in making affiliations and collaborations. Each government has brought their own resources to bear, and we try to facilitate work together because just as it is multidisciplinary, it is also a field of study that requires the entire expertise of the entire globe really to bring to bear on this. It is a bold question that we ask, and it requires everybody.

Dr. SEAGER. I will give you just a very specific example, we try to collaborate where we can within ITAR for international space technology but we have a special example coming up, and that is the starshade technology. We may see a scenario in a very budget-constrained environment where here in the United States we build the starshade. We are leading that technology right now. But we get the telescope and launch from international partners. So that is a way that we could actually accomplish this in the near term.

So in general, it is often challenging to work with other countries for a variety of reasons but in this case we may want to figure out how to do that.

Dr. DICK. Yes. The NASA History Office has just come out with a new book on international cooperation with NASA over the last 50 years, and it is really an important book, I think, because it shows what can be done if we do cooperate. I would have to agree with Sara that it has become more and more difficult to cooperate, especially because of ITAR, the ITAR regulations, and I have been told by people involved that the Cassini program, for example, today probably could not be done because of the ITAR regulations, which were not in effect during the time that Cassini was built.

Ms. JOHNSON. Thank you very much. I yield back.

Chairman SMITH. Thank you, Ms. Johnson. The Chairman Emeritus of the Committee, the gentleman from Texas, Mr. Hall, is recognized.

Mr. HALL. Mr. Chairman, thank you, and I will tell you, as I look at this aggregation of witnesses, you have really done a good job. I don't believe I have ever seen so much intelligence at one table and so much interest that we have, but I will warn you that when I was at SMU, you were the very type of people that I didn't like. You ruined the curve for us ordinary people. But I always respected you.

And Chairman, thank you. This is really interesting, and it takes me back about 15 years ago when we had a hearing on asteroids and found out during the hearing that an asteroid had come within 15 minutes of us sometime during the 1980s and we didn't know how many jillion miles that was but it sounded kind of threatening to me.

But you have such an interesting study and you seem to be so interested in it. I appreciate that.

I guess my first question is, how would you characterize the importance of astrobiology in the general area of STEM education that we have gone through and created and worked on and nurtured here? Second, how would you motivate students, how are you going to get them close to what the other witnesses asked? It really should be easy, I guess, to answer but how do you motivate students to pursue a career in astrobiology research?

I guess Dr. Voytek, you might give me a quick answer to that.

Dr. VOYTEK. I think that the topic of astrobiology is so exciting and encompasses so many different aspects of science, technology and inquiry that we almost have to do nothing but present the topic for people to be engaged and excited and kids to—I believe it is one of the most exciting areas of research for children, and my own experience has been, it requires almost no encouragement. It is an inspiration.

Mr. HALL. Well, I think you have the same problem that we have, this Congress has had at the last probably three or four Presidents asking them for more money for the thrust in space, you know, and if we had had just X number of millions or billions, why, we might not be begging Russia for a ride there and back up to the

Space Station. But you must wake up every morning wanting to go to your work as exciting as it is and excited as you feel.

Professor Seager, let me ask you this. You stated in your testimony that "As a Nation, we must continue to be bold in our space endeavors so as not to only inspire the next generation but also to keep a skilled workforce at the forefront of technology." Do you feel that we are being bold enough or too bold in meeting those goals, or can we be too bold in meeting such an important goal?

Dr. SEAGER. Well, since you said it first, I will say we can never be too bold. As we all know, China is headed to the Moon right now as we speak, and we see China as, you know, in the academic world, they are great at copying everything but we haven't seen them really innovate. But you never know what the future holds.

I will say that most of my students now—and I do work with a lot of engineering students—they do not go on in astrobiology or exoplanets nor do we want everyone to do that. Many of them go out to work in civilian space science or civilian industry or even for defense. So recruiting all these people through their interest, they want to work on really hard problems that have some impact, and you wouldn't know how many of these people, they come to work on these problems because they loved Mars as a child or, you know, they like the idea of searching for life beyond Earth. No, I don't think we can be too bold.

And it is not only inspiring for the public but it draws in the people, those very people that, you know, make the curve higher. You want them to come and to work on our hardest problems for either science or for defense-related technology.

Mr. HALL. I just don't know how I am going to tell my barber or folks in my hometown about your testimony here, but you must really enjoy getting up every morning and going to work, and I thank you for what I call revolutionary study and presentation here.

Mr. Chairman, I yield back.

Chairman SMITH. Thank you, Mr. Hall. The gentlewoman from Oregon, Ms. Bonamici, is recognized.

Ms. BONAMICI. Thank you very much, Mr. Chairman, and thank you to the witnesses. I concur with the comments about how inspirational this testimony has been.

One of the issues that I discussed since I joined this Committee early last year was how we could do a better job educating the public about the benefits of space exploration and research, and I know you have touched on this somewhat, but I have to say that particularly now in a challenging budget time when all of these things we are talking about have a price tag, how do we do a better job? How do all of us do a better job with that education?

And Dr. Voytek, I was pleased to read in your testimony about how astrobiology research has benefited everyday lives, and you talked about the technology used in the Deepwater Horizon accident. Also, there was a mention in the testimony about the Mars Curiosity rover, an instrument analyzing art that can help with causes of deterioration of artwork. What are some of the ways that we can go out and convince a skeptical public that we should continue these investments? Please, go ahead, and I would like to hear from all of you briefly and allow time for one more question.

Dr. VOYTEK. Just very briefly, I often discuss our advances and our approach to astrobiology and our big questions as the search for a cure for cancer. It is a big, extremely important question. It is research that has to be done, and even though we have made tremendous progress, we haven't yet cured cancer. We haven't yet found the origin for life on this planet or life elsewhere.

But I think in the process, we have learned even more about ourselves that have led to other improvements in biotechnology and biomedicine, and the same is true for astrobiology because of the types of questions that we ask, and so in addition to the examples that you gave, we also have people working in synthetic biology that have come up with new, rapid—technology for rapid detection of HIV and hepatitis viruses, so there are a lot of advances in biotechnology. Our discoveries have revolutionized and made it possible for people to sequence the human genome. So there have been a lot of big payoffs as we move towards answering these very big questions.

Ms. BONAMICI. Thank you so much.

Dr. Seager and Dr. Dick, briefly.

Dr. SEAGER. I will be brief. I think we need to keep hitting home the message that pure science leads to so many things like the laser, like the human genome, and we need to make that, you know, as clear as possible to as many people as possible.

Ms. BONAMICI. Thank you.

Dr. Dick?

Dr. DICK. Yes, I have actually edited a volume called Societal Impact of Spaceflight, which I recommend to you, and another one will be coming out soon.

There is a lot of talk often about spin-offs but it is not just the spin-offs that you have heard here and other places. It is also the satellite, the navigational satellites, reconnaissance satellites, weather satellites, communication satellites. All of those, of course, would not have happened without the ability to go into space. And then finally, I would say also I find that going around the country, people are very interested in how we fit, what our place is in the universe, and space exploration helps to solve that.

Ms. BONAMICI. Terrific. And I want to follow up on some of the comments that have been made about inspiring and educating the next generation, and I know we have heard "inspiration" used a lot here today and "being bold," and I know Mr. Hall mentioned, Dr. Seager, your comment about the skilled workforce on the forefront of technology.

How do we continue to engage young people, especially at a young age? And I think if you looked at the panel today, most people would think that two-thirds of the women—two-thirds of scientists are women, which is of course not. So how do we continue to get young people involved? Can you recommend any changes to—I am also on the Education Committee—any changes to STEM education, efforts to maximize students' interest? We are talking about things like incorporating arts and design, more hands-on learning. Do you have suggestions about how we can engage more students in STEM education? Dr. Seager, I would like to start with you.

Dr. SEAGER. This is such a huge topic, it would be impossible for me to articulate all my thoughts, you know, in the time that we have. So I may just say I would be happy to talk to you about it at another point. It is a big, big, big thing and we really need to do something new and different.

Ms. BONAMICI. Thank you.

Dr. SEAGER. I will just say that all children are born curious about the world, and somehow that ends up getting squashed out of them, and so we really have a problem.

Ms. BONAMICI. Thank you. We will definitely follow up.

Dr. Voytek?

Dr. VOYTEK. I just want to say one thing, and I think Sara would agree with me, is that it is extremely important to start as young as possible. If you wait to bring science and technology to students that are in high school or college or even junior high, you have already missed incredible opportunities to develop their interest, their curiosity, and set them on the path in those sorts of careers.

Dr. SEAGER. Yeah, I will just add one more thing. You know, children, we all know, we were all one at some point, they love dinosaurs. You know, often children love space and planets, and we just need to keep that alive and do a better job at it.

Ms. BONAMICI. Thank you.

Dr. Dick?

Dr. DICK. A very specific recommendation would be more curriculum development. There are a few curricula on life in the universe, which, you know, it pulls in everything. One of the great things about astrobiology, astronomy, biology, chemistry, you can talk about almost anything, and the development of specific curricula that could be used in the schools I think would be a very good way to start.

Ms. BONAMICI. Thank you so much. I see my time is expired. I yield back. Thank you, Mr. Chairman.

Chairman SMITH. Thank you, Ms. Bonamici. The gentleman from Mississippi, the Chairman of the Space Subcommittee, Mr. Palazzo, is recognized.

Mr. PALAZZO. Thank you, Mr. Chairman, and I appreciate our witnesses and their testimony today. This is a very exciting subject, and I agree with everything that you all presented to this panel so far.

Dr. Seager, I love your comments about we cannot be bold enough, and you are talking about investment, and we need to do a better job of investing in astrobiology. So could you expand on those two? Where would you invest, and if you have a limited amount of resources and you had to take from one area to put into another area, feel free to comment on that, but also, and I may open this up to everybody, is that when you have an agency that is so risk-adverse and you throw the word "bold" out there and being different, how do you reconcile those two?

Dr. SEAGER. That is such a great question. I would like to have an opportunity to later on perhaps provide a written response. But I can try to answer it briefly right now.

Okay. So in terms of being bold in space, there is a new huge thing happening, and that is, we call it CubeSats. They are tiny spacecraft that now people all around the world are building and launching. Students can do this. So, you know, risk can change now because we can launch small things cheaply. It wouldn't be very risky with something that is not that costly, and in that way you can kind of educate the university-level people, even down to some special high schools, in a very colloquial way—well, so you know, we have other ways we can do high risk and generate that.

The other question I think was about moving money around. That one I can't answer. I think I——

Mr. PALAZZO. You can't or don't want to?

Dr. SEAGER. Like I said, I would have to give it some more thought. But one thing I do want to say is, what makes our Nation unique is just our ability to innovate, and that innovation is something that we—it is very hard to do because you can't always put your finger on what actually it is. You can't articulate it in a way that can actually be supported. But that is why we ended up, you know, being able to get to the Moon. That is why we end up being, you know, a leader in so many things, and so that is the thing I would try to however possible keep that alive, keep that really, really moving forward here in America.

Mr. PALAZZO. And if Dr. Voytek or Dr. Dick would like to——

Dr. DICK. Let me just bring up human spaceflight. When I was a kid, I was told that we would be on Mars with humans by 1984. Obviously we didn't make it. But I do believe that we should have as a long-term goal to go to Mars, or at least as an initial goal, the moons of Mars. The moons of Mars were discovered just a few blocks from the White House at the Naval Observatory so there is sort of a peculiar American interest in the moons of Mars, which are just a few thousand miles above the surface of Mars and would be a great reconnaissance sort of natural satellite space station for looking at Mars. So I believe we should push towards Mars, maybe the Moon first again and then Mars.

Dr. VOYTEK. I would actually like to take an opportunity to focus mostly on missions and exploration. I think that the important thing of our research program in the Science Mission Directorate is that we actually are able to take risks because the investments aren't on the order of millions and hundreds and millions and billions of dollars to do exploration. We can explore lots of these questions on Earth for, you know, a tenth of that cost, and we are bold and we do take risks and sometimes it pays off tremendously and sometimes we make mistakes, but we try because, again, this is a bold question, we are bold with our scientific portfolio and the research programs.

Dr. SEAGER. I did think of one thing to add, and that is the sort of rise of the, we call it just the private commercial spaceflight world like SpaceX. I think the risk now can be transferred to them in a way, still with some level of NASA support, you know, when you are supporting them going to the Space Station and things like that.

Mr. PALAZZO. Real briefly, I will try to get one more question out.

You know, we talk about budgets up here on Capitol Hill. Our Nation is definitely in a financial crisis, and we continue to fight amongst each other over shrinking discretionary budgets when the largest driver of our deficit and our debt is mandatory spending. So we have to come to terms with that.

But when you have got such great programs like this in competition and national security doesn't actually seen to propel Congress, or this Administration, to act in the best interests of the Nation anymore, what would you think would trigger us to focus more on exploring Earth-like planets and getting more engaged in astrobiology?

Dr. SEAGER. Well, one thing that would help is making that very strong message that it is legitimate science now. You know, we are not like searching for aliens or looking for UFOs. We are using standard astronomy. We are using models that have been used for Earth's atmosphere and planetary atmosphere. So I think making that message that it is really a legitimate field of research is one of the critical aspects.

Dr. DICK. And just the very idea of exploration. I think astrobiology embodies the American ideal of exploration, and I think that really is a goal enough, to inspire the young people and the citizens.

Dr. SEAGER. The one thing that sometimes is very hard to see and communicate is, it is really a long-term investment in our national security and we see it even in industry that civilian space science is like a way you can do stuff openly, and so that is—it is very hard to communicate very, very long-term investment but that is essentially what you are doing here.

Mr. PALAZZO. I see my time is expired. I yield back. Thank you.

Chairman SMITH. Thank you, Mr. Palazzo. The gentleman from California, Dr. Bera, is recognized.

Mr. BERA. Thank you, Chairman Smith, and I will reiterate what everyone on the Committee has already said, fascinating subject.

As someone who trained in biology and then went to medical school, I think, Dr. Seager, you touched on, we are all born with this natural curiosity from the youngest of ages—where did we come from, where are we going, the origins of life, whether it is on the scientific realm, whether it is in our faith-based traditions, and so forth. It is naturally innate to who we are as human beings.

So we don't have to rediscover this. Our children have this naturally. What we have to do is grow that curiosity, and in order for that to grow, we have to dream big. I mean, for those of us who grew up in the 1960s and 1970s with the Space Race, there was a dream. We didn't know how we were going to get to the moon. We didn't know the technologies it would take us, yet we dreamed about going there. And we have got to recapture that American spirit, of dreaming big, of not knowing how we are going to make this discoveries but truly committing ourselves to making these discoveries so that our children, so those next generations of scientists have this natural curiosity. And we can't be limited by saying, oh, we don't have the money here, or yes, we have got financial limitations, but we still have to learn how to dream first and then we can work within those limitations to say what is the best way to use those resources. So that wasn't a question. That was more of a comment.

The question is, when we are looking at the origins of life, when we are looking at the future of worlds and how that affects our own planet, these are beyond country borders, these are beyond nationalities, these are beyond faith traditions. What can we do within the context, you know, if another country happens to discover evidence of life on another planet? We are all going to benefit from that discovery, and it is going to propel us forward.

What is the context where we can work together, because we are talking about big data sets. We are talking about analyzing major data sets. What context at the international level would you like to see in terms of collaboration in the search for life? Dr. Voytek?

Dr. VOYTEK. I would say that we attempt with all missions that are being planned by space-faring nations that we can collaborate with them, either contributing personnel or instruments, so we have a very good relationship with ESA, and they have flown instruments on our vehicles and spacecraft; and the counter is we have flown as well so their ExoMars mission that is planned to launch in 2018, we have an instrument onboard.

Our plan for 2020 is to bring back samples. We are already—we have been working with the international community to figure out how to share the results and participate together in the analysis of those samples. I think that, you know, we have ITAR restrictions but, you know, scientists—science is an area that crosses boundaries pretty easily. There is a natural curiosity, and our scientists are doing a lot of the work for us.

Mr. BERA. Dr. Seager, let us say we do build this next generation of telescope. Again, we are going to—we will be bringing in massive amounts of data and it will take a lot of eyes and a lot of analysis. I know in other aspects, we have allowed those amateur astronomers and the public to go out there and look at this data. Again, that is a way of even getting high school students, elementary school students looking at this, imagining things. What are some contexts in which we can do that again, bring in the entire planet?

Dr. SEAGER. Well, I would like to address it from a slightly different view, and I think it is great for scientists to interact internationally because we don't have a political agenda as scientists. But I think when it does come to space technology, it is just—this is my personal opinion—it is so much more efficient because we don't have this extra layer of bureaucracy and inefficiency to do it all ourselves here in America. However, if the budget realities and practicalities don't allow it, then I support the international cooperation in space technology.

In terms of the big data that is public like the Kepler data, for example, any one of us here, we can download the data, we can look at it all around the world. I think that is really great, and that does make the world come together in a unique way.

Mr. BERA. Dr. Dick, did you want to add anything?

Dr. DICK. I would just say that it very much depends on the scenario when you are talking about international cooperation, whether it is microbial life or intelligent life and the implications of finding that. There are various international organizations that can be worked through like the International Academy of Astronautics, and there is work being done on what we should do if—and what the impact would be if either microbial or intelligent life would be found.

Mr. BERA. Great.

Dr. VOYTEK. Let me say one more thing. I want to reiterate a point that you brought up, which citizen science is incredible. I think it is a way to engage the public. I think we have shown in astronomy, in particular, how it is a tapped workforce that has done tremendous scientific work for us, and I think particularly with telescopic data that we will continue to use it in the future and maximize it. It has been awe-aspiring to me to see how people have just gotten involved and are planet hunters themselves. I think the public is dying to get involved even more.

Mr. BERA. Great. Thank you. I yield back.

Chairman SMITH. Thank you, Dr. Bera. The gentleman from Florida, Mr. Posey, is recognized for his questions.

Mr. POSEY. Thank you very much, Mr. Chairman, and thank you, witnesses. It is fascinating testimony, fascinating written testimony. I hated for it to end actually. I wish you could have added some more pages to your testimony. It is fun to read, very enjoyable. I think, you know, you pretty much indicated that life on other planets is inevitable. It is just a matter of time and funding. Clearly, that is it.

If our species survives long enough and I wonder, a question to the three of you, what you see as the greatest dangers to life on Earth.

Dr. DICK. Well, we have had the recent experience of the fireball over Russia. I would have to say that the asteroid impacts are a danger. There is a range of material coming in. We are in a pinball machine and we are in outer space. And you have all this material coming in and occasionally a larger one comes in, as over Russia, but it is entirely possible, as evidenced by some of the craters on the Earth, the ones that wiped out the dinosaurs, they happened over much longer periods but I believe that's one of the motivations for human spaceflight is to get at least some of us off the Earth in case there is a catastrophic event such as that.

Dr. SEAGER. Well, we do like to believe with, you know, sort of the—in the current—we do like to think with our current resources of monitoring asteroids that we will find something big before it finds us, but that is certainly an important area to keep up.

If I can give my personal opinion, I think overpopulation of our planet is going to be our biggest problem.

Dr. VOYTEK. I would say with all systems that resources, particularly essential resources, can be limiting and so I think as we look other places for alternative energy or other means to support a large population, that that is a threat to our planet.

Mr. POSEY. Okay. You know, conditions on other planets are going to seem harsh at first, and we know in history conditions on planet Earth have been harsh. If we came here or explored Earth 64 million years ago, we would say wow, it is too cold, and if we were 65 million years ago we might say wow, it is too hot. So I guess there is going to be windows of opportunity on the other planets too. Any comment on that?

Dr. DICK. Well, it is one of the great things about this research being done just in the last two decades on life in extreme environments, just how tenacious life is, you know, in extreme temperatures and under the oceans in these hydrothermal vents at extreme temperatures and pressures. You find not only microbial life but these long tube worms. I mean, it is just amazing. It seems wherever conditions are possible and by conditions, I mean, a much broader range than we used to have, that life does arise and arise fairly quickly.

Mr. POSEY. Okay.

Dr. VOYTEK. I would say that we talk about life in extreme environments, and I will note that it is mostly microbial, and it is mostly extreme by our own reference. So it is an anthropocentric definition of what is extreme because in fact we have had the capability to inhabit warm places, cold places because of our technology. We basically bring everything back to conditions that support a comfortable life for humans, and so exploration, colonization on other planets and harsh environments will require that we do the same. We are not going to suddenly develop the capability to live at, over the temperature of boiling water. We will have to make our local environment hospitable to ourselves, and we have that technology now.

Mr. POSEY. Dr. Seager?

Dr. SEAGER. I am going to defer on that question.

Mr. POSEY. Okay. What do you believe was the highest historical temperature on the surface of Earth prior to the extinction of the dinosaurs, Dr. Dick?

Dr. DICK. It is hard to say. That is not my area of expertise. But I can say that on Venus, for example, the temperature is now 900 degrees Fahrenheit with sulfuric acid rain and very harsh conditions, and Mars, of course, is much colder now than the Earth. So one of the goals of astrobiology is to try and figure out how planets that seem to be so similar in the past have diverged.

Mr. POSEY. Dr. Seager?

Dr. SEAGER. One thing I always tell my students is that every day is like a Ph.D. defense. So I actually don't remember that number off the top of my head.

Mr. POSEY. Okay. Dr. Voytek?

Dr. VOYTEK. Ditto. Except that, as you mentioned yourself, Earth has experienced extremes in environmental conditions from the early formation, and so certainly environmental conditions well beyond the limits of human life.

Dr. SEAGER. But these changes do happen very slowly, and we believe that life will adapt.

Mr. POSEY. Thank you all very much for your testimony. Mr. Chairman, I yield back.

Chairman SMITH. Thank you, Mr. Posey. The gentleman from Kentucky, Mr. Massie, is recognized.

Mr. MASSIE. Thank you, Mr. Chairman. I find this topic fascinating.

I have a question that I may ask all of you but I want to ask Dr. Seager first. If you were king for a day and could offer an X-Prize for something in your field, what would it be?

Dr. SEAGER. It would be for finding the nearest Earth-like planet, you know, around the star that is closest to our own planet. So I will try to answer that one more time in a more clear way.

Mr. MASSIE. Yes.

Dr. SEAGER. You know, we would like to know just sort of as a legacy for the future which of the very, very, very nearby sun-like stars have a planet that is like Earth with habitable conditions and surface liquid water required for all life as we know it. So I would offer that prize for being able to find that. That would have to be a prize that was sort of on the order of billions, not just millions.

Mr. MASSIE. Okay. And Dr. Dick, what would you——

Dr. DICK. I am going to stick with Europa, I think, because it is less than a billion miles away, and if we could offer a prize for somebody to get there and find a way to drill down below the ice, we don't know exactly how thick it is but that would be a feat in itself if we could drill down through that ice and see what is below the ice.

Mr. MASSIE. And Dr. Voytek?

Dr. VOYTEK. I am going to pick Enceladus. I would like to offer a prize for somebody to go sample the plumes.

Mr. MASSIE. Okay. Thank you.

And so Dr. Seager, you mentioned a starshade, and this captured my attention and imagination. So is this something that would be deployed in space? Could you describe that just——

Dr. SEAGER. Yes. I didn't mention that. Pretty much we do need to go up to space to get above the blurring effects of Earth's atmosphere. Now, the starshade is something that has been in development for a number of years supported by NASA. The concept actually was first written down in the 1980s by a French physical optics researcher. So would you want me to just elaborate on the starshade?

Mr. MASSIE. Yes, maybe 30 seconds.

Dr. SEAGER. Okay, sure. So first of all, the starshade does have heritage from large radio-deployables in space, okay? Those are like 20-meter structures that unfold into a parabolic shape. A starshade is a flat shape. It is not a circle or a square because that has—light will go around the edges and just cause problems. It has to be very specially shaped. It ends up looking like a flower. Okay. Now, demonstrations have been in the lab of how you would fold up the petals, how they would unfurl, and they have to be—the petals have to be made very, very precisely because remember, we have to block out the starlight to basically better than a part in ten billion.

Now, the starshade would essentially just be like, you know, looking at a single light and blocking it with your hand, and the starshade would have to fly far away from a telescope. You could actually use any type of telescope. Now, this just can't go in any orbit because formation flying is tricky and so you really want to get away from Earth, either in an Earth-trailing or Earth-leading orbit or at what we call L2. So the starshade is—it has been under development and it is ongoing.

Mr. MASSIE. So you have to pick a light to block, Right? So you would——

Dr. SEAGER. Correct.

Mr. MASSIE. —place some bets on a star?

Dr. SEAGER. Well, so we are now in this Committee that I am chairing, the Science and Technology Definition Team, we are spending a lot of time on that exact question. And so the question really is, which stars are you going to go to, because you can move the starshade around the sky or around in space or the telescope can be moving around. You know, there is sort of a scenario where you send up two or three starshades. You always have something going on. There is a scenario where as the starshade is making its way to another—you know, to line up with another star, your telescope is going to be like a very new version of Hubble and doing general astrophysics. So yes, that is a problem but it is not a limiting problem.

Mr. MASSIE. And that would—you would be leveraging the Hubble so——

Dr. SEAGER. So we wouldn't use the Hubble in this case, only because Hubble is in low-Earth orbit and Earth's reflected light is a problem as is Earth's gravity for formation flying. But we could essentially use even—I don't want to use the word, you know, "any old space telescope" because it is still a problem, but the telescope doesn't have to really be special in any way. It just has to be in the right orbit.

Mr. MASSIE. And is there some sort of—I know in itself the concept is bang for the buck but is there within that a bang for the buck version of it that you could do that would prove its concept or give some quick results for——

Dr. SEAGER. I mean, this is something we have definitely thought a lot about and because of the scaling issues like, you know, showing it—okay. It is difficult to do anything in space except the real thing because to demonstrate on the scales required and to get, you know, that one in ten billion, really the real thing. However, there are many things that we can do just on the ground and that are ongoing and need to continue like we call it subscale, smaller versions, demonstrations in the lab. There is, you know, testing in the outdoors. You have to go many kilometers separated. So there are things that we can do. But the problem of finding Earth is so hard, there is really no easier, cheap way to actually do it.

Mr. MASSIE. Thank you.

And Dr. Dick, in my last few seconds I would like to touch on something that you mentioned in your opening testimony is reconnecting that gap between SETI and astrobiology, or it looks like astrobiology has kind of subsumed that space. What is the state of SETI right now?

Dr. DICK. Well, objective 7.2 of the Astrobiology Roadmap does mention biosignatures of technology, which technically is SETI but I think the problem is that NASA does not really support that with funding based on the termination of the SETI program by Congress 20 years ago. So if Congress would wish to get SETI going again with some, with even a little bit of funding, that would be an important addition, I think, to astrobiology because right now it is really an artificial separation. We are looking for microbes, but after that, we are not looking for intelligence with the NASA program.

Mr. MASSIE. Great. Thank you very much. Yield back.

Chairman SMITH. Thank you, Mr. Massie. The gentleman from Texas, Mr. Veasey, is recognized for his questions.

Mr. VEASEY. Thank you, Mr. Chairman.

I have a question for Dr. Voytek, specifically about oil and gas exploration, and your thoughts on—if you think that it is practical that some of the technology that is being adapted can be specifically used to detect leaks at great depths as it pertains to oil and gas exploration, particularly offshore.

Dr. VOYTEK. Yes. So one of the examples I gave in my testimony was a technology that was developed at Woods Hole Oceanographic, and it was a combination of an autonomous vehicle and a mass spectrometer that could detect hydrocarbons, and it was used to identify and map the leak from the Deep Horizon spill. Its original design for the Astrobiology program was to try to search for the source of biogenic gases and chemicals, so to identify the sources in the deep sea from hydrothermal vents and, say, the production of methane or hydrocarbons that were produced by microbes. So, I think that that was a great example of that technology being adapted to a very important environmental problem.

Mr. VEASEY. Thank you.

Do you want to add something? You looked like you wanted to add something, Dr. Dick? Okay.

I did have a question for you, Dr. Dick, specifically about the emergence of astrobiology and how you thought that NASA's early initiatives such as the Viking landers on Mars affect the evolution of research at NASA related to the search for life in the universe.

Dr. DICK. Well, the Viking experiments had a great impact, I think. The biology experiments were three biology experiments, and one of them—one of the principal investigators to this day believes he found biology on Mars but the gas chromatograph's mass spectrometer found no organic molecules on Mars which means you if you don't ever get any molecules, you can't have life. So that sort of put a damper on the Mars program for a while. I think it was something like 15 years at least before we went back to Mars with another spacecraft. So those kinds of things really can have an impact. But now with the rovers that we have, including Curiosity, are looking for those organic molecules. They haven't found any complex organic molecules, maybe some very simple ones, but of course, we have only looked in very specific places. So those specific kinds of events in the development of astrobiology can have a great effect as in the case of the Mars rock ALH84001 in 1996. I think that gave a great spur to astrobiology, the development of astrobiology over much broader program than the old NASA exobiology program which was pretty much limited to origins of life, and that is the astrobiology program that we have today.

Mr. VEASEY. And speaking of that, how does that history sort of inform planning for the next decade of astrobiology research?

Dr. DICK. Well, I think if we find anything on Mars in the nature of organic molecules or other things like that, history tells us that that would have a great impact on funding for the future. So we are all hopeful that such things will be found aside from all the other interesting things that those rovers are finding.

Mr. VEASEY. Thank you. Thank you, Mr. Chairman.

Chairman SMITH. Thank you, Mr. Veasey. The gentleman from Illinois, Mr. Hultgren, is recognized.

Mr. HULTGREN. Thank you, Mr. Chairman. Thank you all for being here. This has been very helpful and very interesting.

I also have the privilege of serving as one of the co-chairmen along with my colleague, Mr. Lipinski, who was unable to be here today, of the STEM Caucus, and all of us, every Member of Congress that I speak with, is passionate about how do we get young people interested in science and technology and space and engineering and mathematics, and clearly this field that you all are talking about is, I think, a great avenue to get young people interested.

One question I would have for you of getting into that is when—looking back in your own history, when was the first time you really were interested in this and kind of made the decision, this is what I want to do personally?

Dr. SEAGER. You know, my first memories are about the Moon and stars, but it wasn't until much—so the seed gets planted early but it wasn't until much later, maybe my late teens, that I realized it was a career choice.

Dr. DICK. I grew up in rural southern Indiana, where it was very dark, so the night sky is what inspired me to start with it from a very young age and it just grew from there, and I would have to say also I was very much influenced by science fiction. One of the things I found when I worked at NASA is, a lot of people in NASA were inspired by science fiction, and those novels about, you know, life on other planets and that sort of thing. So for me, it was from a very early age.

Dr. VOYTEK. And for me, my father was a physician and he gave me his medical school microscope when I was about seven, and I started exploring my backyard and the streams and the refrigerator and the food and saw that life was everywhere. Everything was moving. It was kind of scary for my diet but it set me off for my natural interest in how life persists on our planet.

Dr. SEAGER. One thing you will find from most scientists is, there is one special individual who helped them along. In some of our cases, it was a parent. Let us face it: most kids in America, your parent is not a scientist or a doctor. And in that case, it is a teacher. So we need to have a better way to—I mean, we would all like to see teachers be like the best-paid people in the country to recruit the people who are really the very best, but we really need to find a way to reach the teachers. Our children are just spending, you know, so much of their waking hours in school. Everyone needs to encounter that one special person to enable them.

Mr. HULTGREN. I absolutely agree, and that was really where I wanted to go next is, the idea is, much of this is sparked grammar-school age, so, you know, maybe up to 6th grade, 7th grade, 8th grade, maybe a little bit later in high school when you really see, hey this is something I could pursue. Part of the challenge is, I think a lot of teachers are intimidated, certainly when you start talking about astrobiology. That would be something for a 4th-grade teacher to have to inspire kids. That would be intimidating. And so any ways that we can be providing resources to teachers I think is so important, or even bringing in people like yourselves to be talking to young people to let them know how exciting this is and how their generation could be the generation that makes this great discovery. It could be one of them, and how exciting that would be to do that.

So any way that—suggestions you have and really did want, Dr. Seager, to take you up on your offer of a follow-up of talking about education——

Dr. SEAGER. Yes. Well, I just want to offer three comments. The first comment is that unfortunately, our education system here in

America including universities is the same as it has been for hundreds of years.

Mr. HULTGREN. Yes.

Dr. SEAGER. Number two, children, as you know, they love their—the ones that have iPad or the Internet. The whole big data social media thing is something that could actually be big in schools where the teachers are not up on things. The third thing I keep repeating is, it is very hard for us here to have the long-term investment. The long-term investment is to change the culture for our university undergraduate educated people that they can and should be teachers at the elementary level.

Mr. HULTGREN. Well, and I do think this is the type of thing—you know, again, there is a disconnect with, we want to have, you know, great education for our kids. We also struggle with limited resources that we have got, how do we figure out compensating teachers, getting the right people there, bringing people from the outside who aren't necessarily certified but can inspire to be engaged in the classrooms while bringing business, bringing our laboratories, bringing NASA, every possible way whether through technology or otherwise. You are right, I mean, the door is open like it has never been before to get that into the classroom but we have just got to do it.

Let me switch gears real quickly because, Dr. Seager, I want to ask you a little bit more about the— you mentioned the coronagraph—is that right?—and then also the starshade, and you also mentioned collaborating with the international community as a cost-savings measure on that. I wonder if there is any other countries that are doing work in those specific areas that we should be aware of and has collaboration on such projects already been discussed in the scientific community, and how can we encourage that or push it forward?

Dr. SEAGER. Well, I would say that it is in ESA in Europe. In the past when we were supporting a so-called terrestrial planet finder mission, we did have an agreement with the Europeans. I forget the other part of your question.

Mr. HULTGREN. Well, it was just if there is—so it sounds like Europe is open. Has that already started?

Dr. SEAGER. So Europe has recently made their choice for their next big missions in the coming decades, and they did not choose anything in exoplanets.

Mr. HULTGREN. Okay.

Dr. SEAGER. I think that really just means the door may be open for an international collaboration.

Mr. HULTGREN. Okay. Part of our challenge—I am way over—but I think it is frustrating when we have try and have these international collaborations when we are running on CRs, where we literally don't know month to month if we are going to fund programs. Somehow we have got to get back to regular order. We have got to get back to, I think, specifically with science is pull it out of this year-to-year funding, worse, month-to-month funding.

What I hear is, every other nation has five-year, ten-year, twenty-year fully funded science budgets. When we come and talk to them about collaboration, oftentimes they will laugh back at us because they know we don't even know what is going to happen after

January 15th because that is when the C.R. expires. So we have got some big struggles, would love to have your help on all of these suggestions you would have for us to move forward.

My hope is that you get a sense that there is a desire, that we are excited about this and we want to work with you and want your help to do this well.

So with that, thanks, Chairman, for your graciousness, and I yield back.

Chairman SMITH. Thank you, Mr. Hultgren. The gentlewoman from Illinois, Ms. Kelly, is recognized for her questions.

Ms. KELLY. Thank you, Mr. Chair, and going along with my colleague from Illinois, my question is, I started a STEM academy in my district, but my question, all due respect, Dr. Dick, how do we get more women and minorities involved? Because it seems like, you know, we need so many more women represented and minorities in the field, particularly African Americans. Are there any best practices anywhere?

Dr. DICK. Well, I know that NASA Astrobiology Institute does have summer workshops both for students and for the teachers. I am not sure exactly how you encourage the women and minorities to get involved in that, but I am sure the program could be expanded and in that way you might get more, but I would have to think about it more.

Dr. VOYTEK. Maybe I can speak to our programs. The Astrobiology program actually has a minorities program and we are working with the United Negro College Fund to teach the teachers, and a cascade effect of training and providing role models for students, so that they can see that this is something that I can do. So one of the things that we do is this minority institute program, which brings in scientists to work side by side with other astrobiologists, and they are encouraged to develop curricula to take back to their universities, and we work very closely with Historical Black Universities and other minority-serving institutions.

We also have internships that focus on underrepresented groups, and I would be happy to share with the Committee all the work that we have done up until this point in astrobiology, both with missions and just within our own program, that target curricula development, workshops for teachers and how—the efforts that we have made to make astrobiology part of a STEM approach.

Dr. SEAGER. I will just be brief and say we just need role models. You need children to be able to see people in their own community and schools that plants deeply in their mind, oh, I can be like that. I think that is a big thing. And then we need to change the culture at the higher institutions so that it is okay to be different initially, and then we need critical mass so there is no difference.

Ms. KELLY. I definitely agree with that. We work with 6th, 7th, 8th graders, and they don't even realize what the possibilities are until we expose them to the possibilities, and they are so thrilled with what we are doing, but it is just that we have to move it from school to school. We can't just keep coming back to the same students.

Thank you so much. Yield back.

Chairman SMITH. Thank you, Ms. Kelly. The gentleman from Texas, Mr. Weber.

Mr. WEBER. Mr. Chairman, I have no questions.

Chairman SMITH. Oh, well.

Mr. HALL. Mr. Chairman, I would like to ask one question on behalf of the whole Republican and Democrats.

Chairman SMITH. Of course.

Mr. HALL. Do you think there is life out there? You know, are they studying us, and what do they think about New York City?

Dr. SEAGER. Well, let me just say that in our own Milky Way galaxy, there are a hundred billion stars, and we now believe in our universe we have more than a hundred billion galaxies. So if you just do the math, the chance that there is a planet like Earth out there with life on it is very high.

Mr. HALL. I didn't do the math. There is three things about math I couldn't do, and that is add and subtract.

Dr. SEAGER. Well, if we had more time, we could work it out. But let us just say that the chance for life is very high. The biologists never like us to speculate in that way, but the real question really is, you know, is there life very near her in our neighborhood of stars, and that is the question that we are really addressing for real for the first time.

Dr. VOYTEK. On behalf of the biologists, I think it is fine to speculate. We think that life takes over any chance it gets, and so we believe there is a high probability, and I think that one of the amazing things about our own planet is whether they are looking at New York or some small town in Indiana, the diversity of life here and the way that we have chosen to live our lives is just phenomenal, and I think it goes all the way down from humans to microbes.

Dr. DICK. One of the great things about finding the other planets is that it corroborates what many of us have viewed as a guiding principle that what has happened here in our own solar system has happened elsewhere. A lot of people didn't believe that for a long time until 20 years ago when we started to find the planets, and now we find that they are everywhere. So it is another step, of course, to life and an even bigger step to intelligence but I think the guiding principle holds that what has happened here will happen elsewhere in this huge universe.

Mr. HALL. I yield back.

Chairman SMITH. Thank you, Mr. Hall, a good question to end with, and let me thank you all for being here today. This has been just—oh, I am sorry, the gentleman from Utah, Mr. Stewart.

Mr. STEWART. I have been patiently waiting. Mr. Chairman, I assume you are yielding?

Chairman SMITH. I recognized you, I thought.

Mr. STEWART. Thank you, sir.

Chairman SMITH. We will even give you an extra minute for the oversight.

Mr. STEWART. Well, thank you, and it has been interesting, and Mr. Hall actually jumped on something that I wanted to maybe conclude with, and before I do, I thank the witnesses once again, the panelists. It has been—it is fun to hear something and not to leave a hearing frustrated or like you want to throttle the other side like we do in some of our hearings of course is overly politicized, and I appreciate, you know, the recognition that it is in our human nature to explore and to discover.

I want to come back and just be more specific, if I could. Just very quickly, based on your experience, based on your training and kind of your gut, do you think it is even conceivable that there is not other life somewhere in the universe? Is it even possible?

Dr. DICK. It is conceivable, but I mean, we really don't know. This is why it would be such a great thing to find life on Mars because if you find even microbial life on Mars or that sort of thing at a low level, which is independent at the beginning at life, an independent genesis, that means that life began on two planets very close together where conditions were possible, and you can from that extrapolate out to the rest of the universe. But it is possible if we don't find life on Mars and eventually over the years don't find life anywhere else that it either doesn't exist or it is very rare. Now, you can define "rare" yourself. If one out of a billion stars in our galaxy has life, then you still have 400 planets with life on them, so——

Mr. STEWART. Well, and I want to go kind of quickly on this because I am actually trying to get to a point. Do you believe that there is life out there, Dr. Dick?

Dr. DICK. Yes, I do.

Mr. STEWART. Okay. Dr. Seager?

Dr. SEAGER. Yes.

Mr. STEWART. Okay.

Dr. VOYTEK. Yes.

Mr. STEWART. Okay. I think most of us do. I mean, and you look—as you have indicated here, you look at the numbers, it is impossible almost—okay, forgive me for using "inconceivable" but it just seems essentially that there would have to be somewhere.

And then kind of the presumption here of this hearing is that eventually we are going to discover each other whether we discover them or they discover us or however that process might be, and I think in a lot of these conversations we assume that the discovery might be that we find some basic form of life, something, you know, not at all like us, I mean, bacteria or microbes or whatever there might be, but it is possible as well, isn't it, that we find a more sophisticated form of life? Is that true?

Dr. DICK. Yes.

Dr. VOYTEK. Yes.

Mr. STEWART. Okay. Again, it would have to be at least possible.

Dr. DICK. I will just say that my view is that microbial life would be more abundant than intelligent life because it is harder to get to intelligence, but on the other hand, you have these vast scales of time that have evolved also.

Mr. STEWART. Yeah, exactly.

Dr. SEAGER. There is a chance that intelligent life is very rare and not within our sphere to communicate with.

Mr. STEWART. And that is actually my next question, and that is, what—let us assume that we find life. What do we do then? I mean, do we—do you have conversations about what the next step is? Are there any conversations about how we would attempt to communicate with life, or how does that change things for us in the way we view ourselves?

Dr. VOYTEK. I know that——

Mr. ROHRABACHER. We do that with Twitter.

Mr. STEWART. No, this is intelligent life.

Dr. VOYTEK. We certainly discuss what would be the implications for society, you know, what are the philosophical ramifications, the religious ramifications, and we have funded studies through the dialog on science and ethics and religion, through the AAAS, and so we think about those aspects. I think that—and I will say that—and I don't know about if we have thought about how to communicate or invite them home for dinner or what, but——

Mr. STEWART. So that really isn't either of your—it is not within your realms of considering what we do after we discover it? Is that true? Or do you consider that?

Dr. SEAGER. I don't know if it is the best place for us to talk about it because this is one of the things that is sort of in its infancy and maybe even a bit marginal, but people do talk about it. Maybe you send up an ever bigger space telescope, 50-meter telescope and find more. We need to get pictures and detail of the planet. There are people here on our planet now in our country who want to be able to send a robotic probe to another star with a planet. It would take a very long time to figure out how to do that and to actually get there. But there are conversations going on. They are just not at a really formal or well-articulated level.

Dr. VOYTEK. With the exception of the fact that since probabilistically, we believe it is likely we will find microbial life. People in my field are extremely interested in getting a sample of that and being able to immediately compare it to what life is like here and start abstracting more information about exactly what life is, how do we define it, how is it different, what have they learned on that planet that makes it survive there, what can we learn in our own system. I think that there is a plan as a comparative finding a species or another example and so we——

Dr. DICK. This is exactly what I am working on at the Library of Congress for my year right now. And I would also say that there are protocols, official protocols, which have actually gone through the United Nations about what happens if you find extraterrestrial intelligence. Basically the plan is to confirm it first and then tell everybody, not keep any secrets.

Mr. STEWART. Okay. And that would be interesting, wouldn't it, if some people knew and others didn't.

Dr. DICK. Right.

Mr. STEWART. And as interesting as it is to talk about the discovery, I think the more fun conversation is what happens after that and what we do with that information.

Thank you, and Mr. Chairman, thank you for allowing me the opportunity.

Chairman SMITH. Thank you, Mr. Stewart, good questions.

Thank you again to the witnesses for your attendance today and for speaking about such an interesting and fascinating subject. I think you have enlightened us all, and we look forward to staying in touch with you about the issues involved.

So thank you again. We stand adjourned.

[Whereupon, at 11:35 a.m., the Committee was adjourned.]

Appendix I

ANSWERS TO POST-HEARING QUESTIONS

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Mary Voytek

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Astrobiology: Search for Biosignatures in Our Solar System and Beyond"

Questions for the record, Dr. Mary Voytek, Senior Scientist for Astrobiology, Planetary Science Division, National Aeronautics and Space Administration

Questions submitted by Rep. Lamar Smith, Chairman, Committee on Science, Space, and Technology

1. **Please describe the process for developing the roadmap.**

ANSWER: Astrobiology at NASA has been guided by a community-generated "Roadmap" since 1998. This Roadmap is updated approximately every five years. In 2013, the Astrobiology Program Scientists, with concurrence from the National Research Council (NRC) Committee on Astrobiology and Planetary Sciences (CAPS), decided that it was time to perform a major revision of the Roadmap. Previous revisions relied on small teams of selected, senior scientists. For the current revision, it was decided that a grass-roots approach would better reflect the changes in the community. An online community hub, www.astrobiologyfuture.org, was created to support this new approach. One of the major goals of this approach is to involve the broader astrobiology community and engage them in (online) discussions about these topics.

To kick off the current revision, a series of five broad-topic webinars were held and one important question arising from each was chosen to be the focus of five more single-question events online. Following these online activities, approximately 60 active members of the Astrobiology community were invited to an in-person workshop at NASA's Wallops Flight Facility, where the participants were asked to consider and discuss the type of topics they would like to address in the next 10 years. From this workshop, 23 white papers were developed (now 26 with later additions). Following the workshop, the authors of each of the white papers presented their paper to the community via twice weekly, one-hour webinars and held a dialogue about the contents with all interested community members. After each of these webinars, the papers were then opened up to the community for comments. Currently, we are working to assemble the papers into topic groups, which will lead into our next official in-person event, a workshop with a smaller subset of the community to integrate all of the white papers into a single document.

2. **Has the recent Kepler data on the existence of great numbers of exoplanets in our galaxy influenced the development of the goals laid out in the 2014 astrobiology roadmap?**

ANSWER: Of the 26 white papers that have been produced through the road mapping activity, there are 11 that pertain to exoplanets, demonstrating the interest of the astrobiology community in exoplanets and in studying biosignatures from planets that we may never be able to visit. The Kepler data have also expanded our understanding of the types of planets that may exist –and consequently the types of environments that could potentially be habitable. This interest in exoplanets is expected to grow as facilities for the characterization of exoplanets come on-line. The even more recent announcement by the Kepler team on February 26, 2014 that they have confirmed 715 additional exoplanets should only increase interest in this area of research.

3. What does the astrobiology community expect from the 2014 roadmap?

ANSWER: The 2014 roadmap will serve as a guide for the direction of research for the next 10 years within the astrobiology research community. It will serve to guide research goals and development of technology across a wide range of fields including Earth, space, biological and chemical sciences. The document can help provide justification for the relevance of research proposals that align with the roadmap topics, but it is not intended to limit the research topics that could be funded by NASA's Astrobiology Program. The roadmap may also serve to bring new researchers into the community who may not have previously considered themselves as astrobiologists.

4. What is the expectation in the scientific community about international cooperation in future astrobiology missions? Will these be voiced in the 2014 roadmap?

ANSWER: The community, in general, believes that future missions with astrobiological goals will require international cooperation to share the expense and the talent for developing instruments among the leading nations in science and exploration. International partnerships, from the European Space Agency (ESA) or other partners, could come in the form of contributions of instruments or launch vehicles, but these mission concepts are too nascent for specific expectations.

The Astrobiology Strategic Plan (as the Roadmap will be called) will acknowledge the need for international collaboration in design and conduct of research here on Earth and missions sent to astrobiological targets.

5. What Earth-based research has provided the foundation for the search for biosignatures beyond planet Earth? Was that research federally funded?

ANSWER: There are two ways in which Earth-based research has significantly expanded our ability to search for life on extrasolar planets. First, the fleet of Earth-observing satellites has given us a wealth of information on the atmosphere of our home world, which we have utilized to 'ground-truth' the models and techniques we will use to analyze the atmospheres of other planets. This research, including the relevant data acquisition, is led by NASA, but benefits from similar observations by other space agencies.

For example, NASA's EPOXI mission (a planetary science mission) observed Earth after its primary mission was complete and captured a series of whole-planet images that were completely and accurately recreated by our atmospheric models, using data from Earth-observing satellites. The re-creation led to significant improvements of models currently used to interpret solar system observations, which will be used in the future to interpret exoplanet observations. Similar work is currently underway that utilizes EPOXI observations of Mars and of the Earth from a polar viewing angle.

Additionally, decades of research on the history of Earth have given us the best examples we have of 'habitable and inhabited alien planets' - that is, our own planet, when conditions were vastly different from modern Earth, but known to harbor life. This research has unveiled ways for us to search for biospheres dramatically different from our modern-day planet, including for those on planets without the oxygen we breathe. The basic science upon which this work is based is funded by both NASA and NSF. International partnerships with other science agencies, primarily related to the exploration of specific geologic layers, also exist.

6. **What proportion of astrobiology research conducted in the US is funded directly or indirectly by NASA? Is there any research that takes place without any federal funding?**

ANSWER: At least 80 percent of astrobiology research conducted in the US is funded directly or indirectly by NASA. This effort is augmented by the National Science Foundation, National Institutes of Health, and the Department of Energy. Some for-profit institutes (e.g. J. Craig Venter Institute, JCVI) have made significant contributions in the area of synthetic biology, while several private foundations have made strategic awards to researchers to support limited areas of astrobiology.

Astrobiologists also rely heavily on developments in biotechnology and biomedicine to enhance our own capabilities. In the future, the private sector could help by offering grand challenge prizes as well as better access to patented technologies for non-commercial researchers. Both of these non-federal funding based options could allow our research efforts to move forward more quickly.

7. **How much of NASA's current astrobiology program is focused on researching exoplanets? How much of that research is dedicated to detecting biosignatures in the atmospheres of those planets?**

ANSWER: About five percent of the astrobiology Program budget is focused on understanding planetary atmospheres, defining what constitutes a habitable exoplanet and determining how to detect an inhabited exoplanet. One of the NASA Astrobiology Institute's lead teams, the Virtual Planet Laboratory, focuses on these issues. Additionally, a series of grants from the Exobiology program funds work on the habitability of worlds – to increase our understanding of how atmospheric biosignatures are formed and maintained and how we would go about detecting those biosignatures in exoplanet atmospheres. Our path forward is to continue to expand our collaborations with astrophysicists and astronomers to better define the habitable zone for extra-solar planets as well as to develop instruments, technologies and algorithms to enable their characterization.

8. **What instruments are currently being developed by NASA's Astrobiology,**

Science and Technology Instrument Development program that will help us identify exoplanets and the composition of their atmospheres?

ANSWER: The Astrobiology Science and Technology for Instrument Development (ASTID) Program has funded the development of Dr. Michael Shao's "visible nulling coronagraph" for the direct imaging of extrasolar planets. This technology could address the greatest single technical challenge faced by a future exoplanet characterization mission: blocking of the starlight so we can directly image its planets. ASTID also funds Dr. Sara Seager's initial concept studies on using nanosatellites (satellites weighing between 1 and 10 kilograms) to observe transiting Earth-analogs around bright, Sun-like stars.

Currently, proposals to develop technologies for the identification and characterization of exoplanets are solicited by NASA's Astrophysics Division through the Strategic Astrophysics Technology Program.

9. **How can the U.S. leverage international cooperation to advance the field of astrobiology? What are the costs and benefits of international cooperation? Is the current structure for international cooperation effective?**

ANSWER: NASA pursues international cooperation for a variety of reasons, but it is predicated on the premise that cooperative activities must have scientific and technical merit and demonstrate a specific programmatic benefit to NASA. NASA structures its international cooperative activities to protect against unwarranted technology transfer, take into account U.S. industrial competitiveness, and establish clearly defined managerial and technical interfaces to minimize complexity.

NASA leverages international cooperation to make continued progress toward our shared goals in astrobiology. American astrobiologists collaborate with astrobiologists around the world on data analysis, field research, flight experiments, mission planning, and more. The Astrobiology Program has established relationships with over 14 governmental and non-governmental astrobiology organizations around the world that support research in the origin of life and the search for life in the universe. These affiliations have resulted in collaborations between researchers from many nations, access for US researchers to unique analog sites and participation in field campaigns to analog environments and inclusion of US scientists on non-US missions and *vice versa*. Field sites for astrobiology research have ranged from Antarctica to Alaska, Australia, Canada, Chile, China, Hawaii, Mexico, and Norway, as well as elsewhere in the continental United States. The NASA Astrobiology Institute (NAI) has supported the work of U.S. investigators whose investigations are part of the plan for the European Space Agency's (ESA) ExoMars mission to study the biochemical environment on Mars. U.S. scientists on NAI research teams are collaborating with researchers at universities in Athens, Leeds, Leiden, Oslo, Paris, Taipei, Tokyo, and Toronto, as well as scientists at the Vatican Observatory and the Brazilian Space Agency (AEB). NASA also collaborates with astrobiologists from other nations through international organizations such as the Committee on Space Research (COSPAR) of the International Council for Science.

International cooperation provides a platform to promote the sharing of knowledge and expertise throughout the science community. The benefits to international cooperation are often achieved through the pooling of resources, access to foreign capabilities or geographic advantage, addition of a unique capability to a mission, increased mission flight opportunities, or enhanced scientific return. In almost all instances, each partner funds its respective contribution, and the cooperation is conducted on a “no exchange of funds” basis. While NASA’s international activities are pursued for scientific, programmatic and mission-related purposes, they can also provide significant and broader benefits to the United States. NASA coordinates its international activities through the State Department and interagency community.

NASA has developed guidelines that it follows to ensure that its international activities are as well-structured and effective as possible. Among those guidelines are the following principles. NASA international partners are generally government agencies due to the significant level of investment and legal requirements. Each partner funds its respective contributions, but contributions need not be equivalent. Cooperation must be consistent with foreign policy objectives of each partner.

The current structure for international cooperation is effective. NASA’s international commitments are documented in written, binding agreements, which are closely coordinated with the U.S. Department of State and other U.S. government agencies. Our International Agreements are tools that clarify responsibilities of the partners; confirm commitments and terms; document the *quid pro quo* and benefits of the cooperation; confirm arrangements to meet international obligations, such as UN Registration Convention, if necessary; and protect investment and interests, such as technical data rights, intellectual property rights, allocation of risk through a cross-waiver of liability; and provide for the import and export of technical data and goods.

10. How do today's students find their way to astrobiology? Do they learn about astrobiology in their astronomy and biology classes? Do they set out wanting to study astrobiology?

ANSWER: Many students first hear about astrobiology via nature programs on television, popular culture (movies, books), exhibits at museums or news of exciting finds by NASA and other space agencies. In general, it appears as if students are not formally exposed to astrobiology until they are in high school or college. NASA astrobiologists interact with many teachers through our Education and Public Outreach (E/PO) programs - most of which are single-discipline teachers (e.g. astronomy, chemistry, biology, geology, physics). Together we have developed strategies and lesson plans to use astrobiology as an exciting “hook” or theme to both teach the fundamental concepts as well as explore new content in an interdisciplinary way.

In addition, NASA often receives emails from young people around the world, mostly high school and undergraduates, who request advice on how to pursue astrobiology as a career. We have created a ‘career path suggestions’ document that advises them to pursue a graduate degree (M.S. or Ph.D.) level in a single science discipline and recommends approaching astrobiologists who are active in the community to discuss joining their labs. We also provide them with links to existing university programs/hubs, astrobiology related newsletters, social media, etc. as well so they can become involved with the community right away. For reference, the astrobiology career path suggestions is at http://astrobiology.nasa.gov/careers/astrobiology-career-path-suggestions/ and the education resources at http://astrobiology.nasa.gov/education-resources/.

Other successful recruitment and retention tools include the social media group, saganet.org, and the popular Coursera course on astrobiology. Saganet.org was created by astrobiology graduate students and post docs and over time this effort (which now has 916 members) and other social media will help feed students into the pipeline. Meanwhile, the Coursera course on astrobiology has attracted over 35,000 participants. Over the years, NASA has also had about 40 people participating in the Astrobiology Education and Training group, all of whom were incorporating astrobiology into their curriculum.

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Astrobiology: Search for Biosignatures in Our Solar System and Beyond"

Questions for the record, Dr. Mary Voytek, Senior Scientist for Astrobiology, Planetary Science Division, National Aeronautics and Space Administration

Questions submitted by Rep. Eddie Bernice Johnson, Ranking Member, Committee on Science, Space, and Technology

1. **Looking back at where the field was 10 years ago, has the pace of progress in astrobiology been slower or faster than expected, and why? What, if anything, has surprised you about the progress in astrobiology research over the past decade, and how, if at all, should those surprises affect how the community develops future goals?**

ANSWER: In 1996, *Science* reported researchers had found evidence of traces of life from Mars in the meteorite collected in Antarctica, ALH 84001. These findings stimulated a heated and productive debate amongst researchers in planetary sciences and astrobiology. Since then, new and highly motivated researchers have flocked to respond to astrobiology research opportunities. In general, these ambitious researchers have improved our understanding of the definitions of life, what scenarios were possible for the origin of life on Earth and beyond and defining what constitutes a habitable environment. Their greatest contribution has been to challenge how we identify life and how we have identified potential biosignatures. They have been responsible for the discovery of new biosignatures and the verification of the efficacy of potential biosignatures to be used to search for life in our own past as well as beyond the Earth.

Our understanding of the potential for habitable worlds outside our own solar system has been profoundly impacted by the findings of the Kepler Mission. The pace of discovery has been exponential, and the data from the Kepler Mission has advanced the field tremendously over the last 3-5 years. These findings have also fed forward into activities associated with defining the science requirements for any future exoplanet missions.

2. **How has our increasing understanding of how microorganisms survive in extreme environments on Earth affected the types of questions and investigations on the possibility of past or present microbial life on other planetary bodies? How can Congress assess the effectiveness of the linkage between terrestrial research and that enabled by NASA's planetary science missions?**

ANSWER: One of the more significant outcomes of studies on the Mars meteorite ALH84001 was a more critical look at our own understanding of the evidence for life on early Earth. This has revamped the paleontological community, for the better, moving them toward increased scientific rigor in determining what constitutes evidence of life. Research on the terrestrial environment has greatly informed how we should approach the search for life on another planet. A concrete example is the issue of detecting high-molecular weight organic compounds. Work in the Atacama Desert demonstrated new chemical techniques that could increase detectability 100 fold. In addition, with the discovery of perchlorates on Mars (Phoenix, Curiosity), experiments on Atacama soil have replicated the Viking experiments and provided a working model for the current organic detection experiments on Curiosity.

The Planetary Research & Analysis (R&A) program funds analogue research using instrumentation developed with specific planetary missions in mind and sometimes with actual hardware developed for upcoming missions. Analogue research involves sample acquisition and delivery, sample analysis, and operations in relevant, often extreme, environments such as the Dry Valleys in Antarctica or the Svalbard islands in the Arctic. The Astrobiology Science & Technology for Exploring Planets (ASTEP) program funded teams for several of Curiosity's instruments to test them in Mars-like environments here on Earth prior to Curiosity's arrival at Mars. The successful results reported from Curiosity's science investigations, that is, the discovery of an ancient, wet, neutral pH environment that is habitable is a testament to the efficacy of the astrobiology analogues program.

Initially, the field of astrobiology was viewed with suspicion and in some science communities it was thought to be a marketing tool to “sell” one’s proposal. Today Astrobiology is the *raison d’etre* of many planetary science missions, including the driver behind a sustained Mars program and the next mission to the outer planets.

3. **Given the diversity of solar system environments and the likely diversity of conditions on exoplanets, can the field of astrobiology establish a common set of scientific priorities and objectives to determine habitability or do the questions need to be framed differently based on the particular body and environment being studied?**

ANSWER: Fundamental issues of what makes an environment habitable (for example, inventories of elements required for life or sources of energy) will be applicable to all environments we investigate but the specific solutions or details will vary depending on the system. We have made great progress in the identification of the fundamental requirements for life; the major challenge we now focus on is those solutions, primarily pushing the limits to the options possible.

Astrobiologists have a set of scientific priorities and objectives to determine habitability on extrasolar planets, specific to global surface biospheres. This means our preliminary targets will be similar to Earth. However, as our capability to search increases, we will also be able to constrain habitability and search for life on planets with more extreme conditions, such as ice-covered worlds, planets dominated by organic chemistry, or worlds of a type that we have not yet encountered in our explorations.

4. **What is the status of current efforts to update the Astrobiology Roadmap and how likely will the new Roadmap alter the priorities for scientific research? What would be the impact of an independent strategy for astrobiology scientific research, as directed in recent NASA authorization bills vis-a-vis the Roadmap?**

ANSWER: Currently, NASA is nearing the final stage of the Astrobiology Roadmap activity and we are anticipating producing a final document by April 2014. Throughout this latest revision process, NASA has received numerous inputs from the community to the roadmap, at the in-person workshop to outline important topics, creating and discussing the white papers for these topics, and we are depending on community input to help with our next and final step, the integration of these white papers into a single document. We expect that the new Roadmap will alter research priorities based on advances in astrobiology over the last decade. The updated document will not be used to limit the research topics that could be funded by NASA's Astrobiology Program; however, for those studying the topics outlined in the Roadmap, it will provide strong justification for the relevance of that research. Any independent strategy for astrobiology scientific research (such as might be formulated by, for example, a committee of the National Research Council), will likely plow the same ground as the current revision since a broad cross-section of the astrobiology community, in the US and abroad, has been involved in the creation of the new Roadmap. The astrobiology community as a whole has developed all of the topics to be covered, the research directions to be pursued, and the connections between research objectives within the updated document. Moreover, the National Research Council, as well as the Planetary Science Subcommittee of the NASA Advisory Council's Science Committee, will be asked to review the Roadmap and astrobiology is a subject area covered in the latest Planetary Science Decadal Survey. The creation of an independent strategy would likely involve the same or some subset of the participants, therefore, would likely be duplicative. An independent strategy would also be a costly undertaking and likely require years for completion.

5. **How does NASA ensure that astrobiology scientific priorities are adequately integrated into NASA's overall planetary science priorities?**

ANSWER: The highest priority, large-class missions from the most recent Planetary Science Decadal Survey are both astrobiology focused - Mars sample return and Jupiter Europa Orbiter. These missions have evolved into the Mars Rover 2020 and Europa mission concept studies. Consistent with NASA practice, our Research and Analysis program reflects the priorities in the overall planetary science program (showing relevance to the scientific goals of the program is a selection criterion). The current reorganization of the Research and Analysis (R&A) programs in NASA's Planetary Science Division (PSD) reflects the importance of funding of research in the area of habitability to inform PSD missions. For example, if funded, a Europa mission would conduct detailed reconnaissance of Jupiter's moon Europa, investigating whether the icy moon could harbor conditions suitable for life.

Although most of the expertise to detect and image extrasolar planets resides within NASA's Astrophysics Division, the expertise to interpret those data in order to understand the potential for habitability and the presence of biosignatures resides primarily within NASA's Planetary Science Division (PSD). The current reorganization of the R&A programs in PSD takes advantage of both sets of expertise, by establishing an exoplanets research program which is jointly managed and funded by Astrophysics and Planetary Science.

6. **What challenges are associated with maintaining the multi-disciplinary expertise necessary for carrying out astrobiology research and what can be done to facilitate the continuity of the expertise?**
   a. **How do new discoveries in the disciplines contributing to astrobiology feed into ongoing astrobiology research?**

ANSWER: In order to preserve the depth and integrity of any given discipline, astrobiologists typically need to proceed directly to the Ph.D. level (and likely beyond) in a single science discipline. Astrobiologists come to the interdisciplinary/collaborative field as a representative of, and expert in, a primary (although often broad-based) discipline – but can do so with an open mind and often significant background in another, secondary discipline. Programs like the University of Washington's graduate certificate in astrobiology; Pennsylvania State University's dual-title Ph.D. in astrobiology, and all-plenary conference formats facilitate an astrobiologist's continued professional development and builds fluency in secondary disciplines.

Our Program's continued focus on the next generation is key. Even in lean times, NASA has made it a priority to ensure funding is available for Ph.D. students and post docs to present at conferences, finish their projects, travel to spend time with new collaborators and conduct field research. We have also made efforts to encourage scientists in a single discipline to see where they fit within an interdisciplinary project and help them understand the contributions they can make as well as establishing balance within projects.

Often the multi-disciplinary expertise in Astrobiology is maintained through connections between different principle investigators and different research groups, not within individuals, and for this the most important thing is to continue supporting workshops, conferences and symposia that bring together these different scientists. In the course of developing the new Roadmap, it became quite clear that the really interesting questions in astrobiology are connected to each other in a complex web of relationships. New discoveries in the fields contributing to astrobiology can change these connections or even change the questions. These discoveries are often carried into astrobiology by their original discoverers since many leading researchers in those traditional disciplines that comprise astrobiology consider themselves to be astrobiologists, too, and actively participate in NASA's Astrobiology Program (Exobiology, NASA Astrobiology

Institute) and through astrobiology-focused meetings (e.g., AbSciCon, Origins).

7. **What has been the impact of NASA's Astrobiology Institute on furthering astrobiology research, expanding knowledge, and training scientists? What are the pros and cons of increasing the number of teams comprising the Institute?**

ANSWER: NASA's Astrobiology Institute (NAI) was established in 1998 and has been essential in developing the environment for interdisciplinary research to flourish. The NAI's success has firmly established the interdisciplinary approach in Astrobiological research as the common mode of operation - whether proposals go to the Institute or the other elements of the Astrobiology Program. Our experience with the NAI, which funds large teams for five years, has demonstrated that certain research problems can be handled in a traditional award (1-3 Co-investigators operating within three years) and others are best undertaken with a large group for a longer period of time. Overall, the Astrobiology Program needs a balance of small single investigator projects and projects with larger teams.

At this stage in the evolution of the NAI, it is the size of the NAI teams that has most significantly affected the scientific impact of the research accomplished by the funding invested. The Central Node of these teams is currently hosted at Ames Research Center and their primary functions are to disseminate the research results of the teams, to provide an outward face of the Astrobiology Program, and to continue activities targeting recruitment and retention of individuals in the astrobiology discipline.

The NASA Astrobiology Institute has played a central role in developing a new generation of scientists who consider themselves astrobiologists first and scientists from a 'home discipline' second, creating a community of practice for the field. This has occurred through conferences, white papers, and proposal-writing workshops aimed at the early career community.

Meanwhile, the NAI is motivating the next generation of scientists with an Education and Public Outreach (E/PO) portfolio that integrates similar techniques across the wide variety of research conducted by the institute. In the past, our criterion for selecting teams has included E/PO proposals, which were judged on the assessment of program impacts and the degree to which the programs increase STEM participation of underserved/underrepresented minority groups.

The inherent NAI structure of five-year cooperative agreements wherein the awarded organization has to invest longer-term resources has facilitated many universities to create new departments and positions in astrobiology. Over the years, these efforts have laid the foundation for a strong, regionally based yet nationally coordinated infrastructure, which is able to support new hires – from undergrads to tenure-track faculty. NAI's central coordination has enabled the whole astrobiology community to take advantage of these opportunities.

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Responses by Dr. Sara Seager

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Astrobiology: Search for Biosignatures in Our Solar System and Beyond"

Questions for the record, Dr. Sara Seager, Class of 1941 Professor of Physics and Planetary Science, Massachusetts Institute of Technology

Questions submitted by Rep. Lamar Smith, Chairman, Committee on Science, Space, and Technology

1. What is the expectation in the scientific community about international cooperation in future astrobiology missions? Will these be voiced in the 2014 roadmap?

Please see response to question 3 below.

2. Due to budget constraints, we're in a fiscal environment where we must prioritize our spending. What is our most important technical priority in order to further our understanding of exoplanet atmospheres?

It would be remiss not to mention the technological capabilities of the James Webb Space Telescope (JWST) to study the atmospheres of a special subset of exoplanets, the transiting planets, those that are fortuitously aligned to go in front of their host stars. Please see my written response to Rep. E. B. Johnson's question 5, for more on the JWST.

The most important technical priority is to complete the development of starlight suppression techniques for space-based telescopes to reach a level capable of studying giant planet down to Earth-size planet atmospheres. The background reasoning is that exoplanets and exoplanet atmospheres are not only faint but also are so close to their host stars that the glare from the star overwhelms the planet light. The starlight must be suppressed, or in other words, blocked out, so that the planet light can be detected.

Specific details for technology priorities for starlight suppression techniques are provided by NASA's Exoplanet Exploration (ExEP) office by way of a recently completed Exoplanet Exploration Program Technology Plan by which can be found at the following url:
http://exep.jpl.nasa.gov/files/exep/2013%20Tech%20Plan%20Appendix%20Preliminary.pdf . The technology gap list is provided for two different starlight suppression techniques, the starshade (i.e., external occulter) and the coronagraph (i.e., internal occulter).

An equally important technical priority for the future study of exoplanet atmospheres is to invest in large mirrors in space, of 10 m class in telescope mirror diameter or larger. A larger collecting area will eventually be required to both survey a suitable number of stars for exoplanet discovery and to have capability to study exoplanet atmospheres of all kinds.

On a separate point of high relevance, many technologies developed for defense purposes take a long time to reach civilian applications. Accelerating the release of information where possible could lead to major cost savings.

3. How can the U.S. leverage international cooperation to advance the field of astrobiology? What are the costs and benefits of international cooperation? Is the current structure for international cooperation effective?

It is my personal opinion that international cooperation is only helpful where expertise is lacking in the US. Speaking to my field of expertise, exoplanets, we have all the expertise required here in the US. One exception is the geographic placement of large ground-based telescopes in dry places such as the dry mountain deserts of Chile and the radio quiet zone of Australia. In my personal opinion, the costs of international cooperation are high enough to slow research down through various bureaucratic barriers. An alternate view is that to cut costs for costly space telescope missions, international cooperation should be encouraged. Please see also the response to question 4 below.

4. In your written testimony, you recommend NASA continue development of both an internal coronagraph and a starshade for use with a telescope to discover and categorize exoplanets. You also mention collaborating with the international community as a cost savings measure. Are there countries actively developing these technologies? Has collaboration on such a project already been discussed in the scientific community?

Both the internal coronagraph and the starshade have strengths and weaknesses such that both technologies should continue to be matured. The ideal space-based direct imaging planet-finding mission might use both technologies.

My recommendation for international collaboration in my written testimony is highly specific and limited to the starshade concept for a space telescope mission because the mission is modular. In my personal opinion, the modularity could help to avoid bureaucratic and related technical "costs" and inefficiencies. The starshade and its spacecraft can be developed, built, and launched by the US. The observatory (the telescope, instruments, and spacecraft), a straightforward but still costly component of the overall mission, could be developed and launched by international partners. Note that the starshade and telescope could be launched together, even by an international partner launch, further saving costs. This collaboration would be a clean separation of mission components.

The US is in a leading position exoplanet direct imaging from space. No one outside of the US is working on the starshade. Regarding the internal coronagraph, US expertise leads the world with wavefront control at the required planet-star flux contrast levels for giant planets or for smaller (i.e., rocky) planets. (As a counter point let me mention that

Europe appears to have seized the lead from the U.S. in other astronomy-related topics of dark energy, X-ray, and gravity waves). Japan has shown some interest in direct imaging for planet discovery but has not yet reached the same expertise as the US in coronagraphy with precision wavefront control.

Speaking to international collaborations on exoplanet discovery via space-based direct imaging. Collaboration has not been discussed recently although in the past (circa early 2000s) there were parallel studies of starlight-blocking space telescope missions in the US and Europe, with extensive scientist-to-scientist discussions and mission design coordination, but no formal NASA to ESA agreements. If the projects had matured further (before funding cuts) formal agreements may have materialized between the US and Europe and possibly Japan.

5. How do today's students find their way to astrobiology? Do they learn about astrobiology in their astronomy and biology classes? Do they set out wanting to study astrobiology?

In my experience with graduate, undergraduate, and some high school students, I have found that the students learn about astrobiology via the news and social media or through parents or adult friends or relatives. Today's young people are remarkably savvy and more connected to the world by virtual electronic media than every before.

6. In your oral testimony, you mentioned that you have given a great deal of thought to STEM education. Would you please expand on your comments?

This topic is one for extensive discussion and if any of the members would like to talk further please have them contact me directly. The overview is three pronged. First, that schools have outdated educational philosophies dating back for decades if not a century. Second, related, is that students need to be self engaged and guided to follow their interests and motivation and partake in hands on activities. Third, role models are critical.

Questions submitted by Rep. Eddie Bernice Johnson, Ranking Member, Committee on Science, Space, and Technology

1. Looking back where the field was 10 years ago, has the pace of progress in astrobiology been slower or faster than expected, and why? What, if anything, has surprised you about the progress in astrobiology research over the past decade, and now, if at all, should those surprises affect how the community develops future goals?

Speaking to my field of exoplanets, the surprising progress has been outstanding for two reasons. The first is the investment in technology. The best example is the success of NASA's Kepler Space Telescope. Kepler performed measurements at levels 100 times or greater improvement over anything previously and thus opened up a new "window" on exoplanet discovery. Investment in technology in many areas has been critical for the field of exoplanets moving forward as rapidly as it has. The second reason is the attraction of exoplanet research to young people going into the field. Arguably many of the brightest young people with high potential are going into the field of exoplanet (and astrobiology) research.

2.Your prepared statement uses the term "inferred" on several occasions. Can you explain whether corroborative research is viewed by scientists as needed when observable evidence is not possible due to technology constraints and only inference is possible, such as the inference of planetary temperatures and clouds?

You are correct to point out there are two cases where "inferred" is appropriate in science in general. The first is where technology limits measurements and with more advanced technology and thus better measurements "inferred" can turn into "detected". The second instance is where the usage of "inferred" means because of the nature of the measurements, one can never be 100% certain and thus the word "detected" is inappropriate. In my testimony I only used the term "inferred" to mean where remote telescopic observations of a distant planet, no matter how sophisticated, cannot provide enough information. For example, using atmospheric observations we cannot detect liquid water oceans directly. But atmospheric water vapor is a nearly definite sign of liquid water oceans on a small rocky planet; without oceans water vapor should not be present. Just to be careful we use the phrase "can be inferred" rather than "can be detected" in such a case.

The surprises have shown us that we have as a nation what it takes to make impact and discovery in astrobiology related fields.

3. Given the diversity of solar system environments and the likely diversity of conditions on exoplanets, can the field of astrobiology establish a common set of scientific priorities and objectives to determine habitability or do the questions need to be framed differently based on the particular body and environment being studied.

The set of definitions of requirements for life (or, habitability) have been defined by the National Academy of Sciences National Research Council report on the "Limits to Organic Life in Planetary Systems". The information is provided in the report's Executive Summary which can be found at the following url. Regarding different planetary bodies, the scientific measurements and hence priorities may differ as to how to determine whether the criteria for habitability are met.

4.What challenges are associated with maintaining the multi-disciplinary expertise necessary for carrying out astrobiology research and what can be done to facilitate the continuity of expertise?

Continued funding of the NASA astrobiology programs is the most natural way to maintain the multi-disciplinary expertise. Continued training of undergraduate, graduate, and postdoctoral researchers will facilitate the continuity of expertise. People go where the money is and related astrobiology programs force researchers from different disciplines to have an ongoing dialog.

4a. How do new discoveries in the disciplines contributing to astrobiology feed into ongoing astrobiology research?

The process of scientific exploration is challenging to articulate but new discoveries always raise new questions which fuel further research.

5. Through observations from NASA's Kepler mission and ground-based telescopes, hundreds of new planets and planet candidates have been identified. The TESS mission, which you discussed in your testimony, will add to the population of new planets identified. Given the large number of planets being discovered through ground-based and space-based observations, how will researchers prioritize which ones offer the most "bang for the buck" in terms of more detailed studies by the James Webb Space Telescope, which is planned for launch in 2018, or by other observatories?

The TESS team (on which I am a co-Investigator) will give priority to planet candidates that could be rocky planets with thin atmospheres to find out if any have resemblance to the terrestrial planet sin our own solar system. If TESS discovers any rocky planets in the habitable zone of their host star (a possibility for small stars), those candidates will be made of the highest priority for follow-up obsrvations by the TESS team. As an international facility, the James Webb Space Telescope has a competitive, peer-reviewed process for telescope allocation time. The same is true for other national and international telescope facilities. The expectation, therefore, for any other class of planets, is for the best science to be accomplished in a "free-market" fashion.

Responses by Dr. Steven Dick

Responses to Questions for the Record
From Astrobiology Hearings at House Science Committee
December 4, 2013

Dr. Steven Dick
Baruch S. Blumberg NASA/Library of Congress Chair in Astrobiology
Kluge Center, Library of Congress

Questions from Rep. Lamar Smith

1. What do you think is the immediate "next step" in astrobiology research? Is there disagreement among experts in the field about what the next step should be?

Astrobiology today almost entirely addresses microbial life, leaving out complex and intelligent life. The microbial aspect is quite robust via the NASA program and its international partners, and has significant momentum with its ongoing discoveries. But the search for more complex life involves an expanded scientific community. I would like to see an immediate next step that re-integrates the search for microbial and more complex life. The most immediate next step in this re-integration is an expansion of work on biosignatures, to include not only atmospheric but also technological biosignatures such as electromagnetic signals. This is especially relevant as more exoplanets are discovered, including Earths and Super Earths.

2. How much has been accomplished in fulfilling the seventh goal of the 2008 astrobiology roadmap, particularly determining "how to recognize signatures of life on other worlds…?"

Considerable progress has been made in the last few years in fulfilling parts of Goal 7 related to biosignatures. On Earth scientists have recently reported evidence of microbial life in 3.48 billion year-old rocks in Australia. On Mars they have found evidence of a warmer and wetter Mars in the past, and simple organics, but so far no evidence of life. Beyond the solar system, the recent discovery of numerous exoplanets has allowed the development of techniques to probe the atmospheres of those planets. As I mentioned in my testimony, the best and most unambiguous biosignature would be a signal for extraterrestrial intelligence. This falls under Objective 7.2, biosignatures to be sought in nearby planetary systems "that can reveal the existence of life or technology through remote observations." Progress has been slow and sporadic in this "SETI" endeavor, which is not funded by the federal government and relies on sporadic private funding. Encouragement from Congress, which terminated the NASA SETI program in 1993, could give an immense boost to fulfilling this objective, and repair the artificial divorce that now exists in the NASA astrobiology program between searching for microbial life and more complex life. Some of the latest thinking on biosignatures in the context of the Astrobiology Roadmap may be found at
https://docs.google.com/document/d/1B_QZHlr_wkaWECvocalomWPWuNplYhbc_67dgbWSlRE/edit?pli=1

3. What does the astrobiology community expect from the 2014 roadmap?

In contrast to past roadmapping, the 2014 roadmap is seeking ideas from the bottom up, involving researchers in the field to a greater extent than before. The details of the roadmapping process and content are at http://astrobiology.nasa.gov/roadmap/ Though I am not directly involved in the roadmapping, this new process should result not only in enhanced techniques addressing current problems in astrobiology, but also in a statement of new areas of research and how to tackle them.

4. What is the expectation in the scientific community about international cooperation in future astrobiology missions? Will these be voiced in the 2014 roadmap?

International cooperation in large space missions, including those for astrobiology, is hampered by current ITAR regulations. It is unclear whether this will be addressed in the Roadmap. The NASA Astrobiology Institute (NAI) does have an extensive network of about a dozen international partners for smaller programs. These international partners and their work are listed at https://astrobiology.nasa.gov/nai/international-partners/

5. Due to budget constraints, we're in a fiscal environment where we must prioritize our spending. What is our most important technical priority in order to further our research of exoplanet atmospheres?

The James Webb Space Telescope is our best space-based bet for probing exoplanet atmospheres in the near future. A modest investment at the level of about $10 million/year could significantly enhance ground-based technology for the most important exoplanet biosignature of all – electromagnetic signals from intelligence.

6. How can the U. S. leverage international cooperation to advance the field of astrobiology? What are the costs and benefits of international cooperation? Is the current structure for international cooperation effective?

Astrobiology should truly be an international endeavor, since its fundamental questions know no boundaries. International cooperation, however, is increasingly hampered by ITAR regulations, especially for complex spacecraft. The United States stands to benefit from the findings of the Gaia spacecraft, launched by the European Space Agency in December, 2013, and scheduled to begin observations of a billion stars, many of which will have exoplanets. The NAI's international partner program is quite effective.

7 How do today's students find their way to astrobiology? Do they learn about astrobiology in their astronomy and biology classes? Do they set out wanting to study astrobiology?

Astrobiology is usually a small part of introductory astronomy classes, less so in biology. Much more work needs to be done to leverage the excitement of astrobiology into the classroom. This could be done through curriculum development undertaken or encouraged by NASA, perhaps in cooperation with partners such as the SETI Institute, the National Science Foundation, the Department of Education, and Biology and Society programs that exist at a number of universities.

Rep. Eddie Bernice Johnson

1. Looking back at where the field was 10 years ago, has the pace of progress in astrobiology been slower or faster than expected, and why? What, if anything, has surprised you about the progress in astrobiology research over the past decade, and how, if at all, should those surprises affect how the community develops future goals?

I would say the pace of progress has been faster on several levels. Ten years ago only a few gaseous exoplanets were known, compared to the thousands now known, some of which are Super Earths. The time is ripe for the search for biosignatures in exoplanet atmospheres, and future goals should push technology for biosignature detection ranging from microbes to intelligence. At the microbial level research on life in extreme environments has brought new surprises in terms of how tenacious life is on Earth, implying life could develop under a much broader range of conditions on other planets than previously thought.

2. Your prepared statement refers to questions on whether there is a general theory of living systems or a universal biology and notes that "the reinstatement of funding for SETI [the Search for Extraterrestrial Intelligence] would allow a systematic examination of these intriguing questions." How is work on SETI currently being funded? Are you suggesting that NASA resume providing SETI funding, and if so, why?

The largest current SETI program is the Allen Telescope Array in California, privately funded largely by Silicon Valley entrepreneurs. However, the funding is sporadic, to the extent that the instrument sometimes is shut down. Only 42 of the proposed 350 antennas have been built due to lack of funding. This seems a rather sad and inefficient way to fund a program that could have great impact on science, the country, and the world, should extraterrestrial intelligence be found. Congress terminated the NASA SETI program in 1993, after only one year of searching. The termination was based not primarily on fiscal or technical considerations, but on the "ridicule factor," before planets were known to exist in abundance around Sun-like stars. In my opinion NASA should take the lead in resuming the search. It is admittedly a low probability – high return endeavor, but it has the support of the majority of Americans, is technically low risk and low cost compared to spacecraft, embodies the American spirit of discovery and exploration, and would infuse more excitement into NASA programs at relatively low cost. (At its 1993 termination the NASA SETI budget was about $12 million per year). NASA has not taken up the search for 20 years, partly because of funding, but also because of the stigma of Congressional termination. Encouragement from Congress, in the form of funding or at least a statement of interest, could reignite this important endeavor.

3. What challenges are associated with maintaining the multi-disciplinary expertise necessary for carrying out astrobiology research and what can be done to facilitate the continuity of the expertise? How do new discoveries in the disciplines contributing to astrobiology feed into ongoing astrobiology research?

The United States should encourage a new generation of astrobiologists, not only in the natural sciences but also in the social sciences and humanities to answer the question asked by one of the Members at the Astrobiology Hearings: "What do we do if we find life?" Such a discovery would affect our worldviews no less than the Copernican worldview gradually changed everything in terms of our perspective on ourselves and our place in the universe. In the natural sciences, new discoveries breed new research, carried out both at NASA and universities. Such is not the case in the social sciences and humanities, which need to look at implications of discovering life beyond Earth, no less than this was a significant activity in the Human Genome Project, nanotechnology, and other areas of frontier science. The impact of science on society is an important endeavor that needs to be nurtured. A beginning has been made by the establishment of the Baruch S. Blumberg NASA/Library of Congress Chair in Astrobiology, located at the Kluge Center in the Library of Congress. More could be done, specifically by encouraging the work of the "Astrobiology and Society" focus group of the NASA Astrobiology Institute, as well as scholars in a variety of disciplines in government institutions and universities.