ASTROBIOLOGY AND THE SEARCH FOR LIFE BEYOND EARTH IN THE NEXT DECADE

HEARING

BEFORE THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
HOUSE OF REPRESENTATIVES

ONE HUNDRED FOURTEENTH CONGRESS

FIRST SESSION

September 29, 2015

Serial No. 114–40

Printed for the use of the Committee on Science, Space, and Technology

Available via the World Wide Web: http://science.house.gov

U.S. GOVERNMENT PUBLISHING OFFICE
97–759PDF WASHINGTON : 2016

For sale by the Superintendent of Documents, U.S. Government Publishing Office
Internet: bookstore.gpo.gov Phone: toll free (866) 512–1800; DC area (202) 512–1800
Fax: (202) 512–2104 Mail: Stop IDCC, Washington, DC 20402–0001

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HON. LAMAR S. SMITH, Texas, *Chair*

FRANK D. LUCAS, Oklahoma
F. JAMES SENSENBRENNER, JR., Wisconsin
DANA ROHRABACHER, California
RANDY NEUGEBAUER, Texas
MICHAEL T. McCAUL, Texas
MO BROOKS, Alabama
RANDY HULTGREN, Illinois
BILL POSEY, Florida
THOMAS MASSIE, Kentucky
JIM BRIDENSTINE, Oklahoma
RANDY K. WEBER, Texas
BILL JOHNSON, Ohio
JOHN R. MOOLENAAR, Michigan
STEPHEN KNIGHT, California
BRIAN BABIN, Texas
BRUCE WESTERMAN, Arkansas
BARBARA COMSTOCK, Virginia
GARY PALMER, Alabama
BARRY LOUDERMILK, Georgia
RALPH LEE ABRAHAM, Louisiana
DARIN LAHOOD, Illinois

EDDIE BERNICE JOHNSON, Texas
ZOE LOFGREN, California
DANIEL LIPINSKI, Illinois
DONNA F. EDWARDS, Maryland
SUZANNE BONAMICI, Oregon
ERIC SWALWELL, California
ALAN GRAYSON, Florida
AMI BERA, California
ELIZABETH H. ESTY, Connecticut
MARC A. VEASEY, Texas
KATHERINE M. CLARK, Massachusetts
DON S. BEYER, JR., Virginia
ED PERLMUTTER, Colorado
PAUL TONKO, New York
MARK TAKANO, California
BILL FOSTER, Illinois

CONTENTS

September 29, 2015

ASTROBIOLOGY AND THE SEARCH FOR LIFE BEYOND EARTH IN THE NEXT DECADE

TUESDAY, SEPTEMBER 29, 2015

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

The Committee met, pursuant to call, at 10:02 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Lamar Smith [Chairman of the Committee] presiding.

LAMAR S. SMITH, Texas
CHAIRMAN

EDDIE BERNICE JOHNSON, Texas
RANKING MEMBER

Congress of the United States
House of Representatives

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
2321 RAYBURN HOUSE OFFICE BUILDING
WASHINGTON, DC 20515–6301
(202) 225–6371
www.science.house.gov

Committee on Science, Space, and Technology

Astrobiology and the Search for Life Beyond Earth in the Next Decade

Tuesday, September 29, 2015
10:00 a.m. to 12:00 p.m.
2318 Rayburn House Office Building

Witnesses

Dr. Ellen Stofan, *Chief Scientist, NASA*

Dr. Jonathan Lunine, *David D. Duncan Professor in the Physical Sciences, Cornell University; Director, Center for Radiophysics and Space Research, Cornell University*

Dr. Jacob Bean, *Assistant Professor, Department of Astronomy and Astrophysics, University of Chicago*

Dr. Andrew Siemion, *Director,SETI Research Center, University of California, Berkeley*

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

Astrobiology and the Search for Life Beyond Earth in the Next Decade

September 29, 2015
10:00 a.m.
2318 Rayburn House Office Building

Purpose

The Committee on Science, Space, and Technology will hold a hearing entitled *Astrobiology and the Search for Life Beyond Earth in the Next Decade* on Tuesday, September 29, in Room 2318 of the Rayburn House Office Building. This hearing will review the scientific methods employed to search for life, examine recent scientific discoveries in the field of astrobiology (the study of the origin, evolution, distribution, and future of life in the universe), and assess the prospects of finding life beyond Earth over the next decade. The hearing will include an overview of NASA's astrobiology programs and NASA's new Nexus for Exoplanet System Science ("NExSS") initiative. It will examine the techniques and capabilities necessary to determine the potential for the existence of microbial life within our solar system. The hearing will also investigate the scientific methods of exoplanet atmospheric spectroscopy and radio and optical astronomical surveys.

Witnesses

- **Dr. Ellen Stofan**, Chief Scientist, NASA
- **Dr. Jonathan Lunine,** David D. Duncan Professor in the Physical Sciences, and Director, Center for Radiophysics and Space Research, Cornell University
- **Dr. Jacob Bean,** Assistant Professor, Departments of Astronomy and Astrophysics, Geophysics, University of Chicago
- **Dr. Andrew Siemion,** Director, SETI Research Center, University of California, Berkeley

Background

Astrobiology is "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] This multidisciplinary field encompasses the search for habitable environments in and outside of our solar system. It also includes the search for evidence of prebiotic chemistry, field research into the origins of life on Earth, and studies of the potential for life to adapt to challenges on Earth and in space.

NASA has been performing astrobiology research since the beginning of the U.S. space program. NASA's astrobiology program currently resides in the Planetary Science Division of the Science

[1] *Assessment of the NASA Astrobiology Institute*, National Research Council Report (2008) http://www.nap.edu/catalog/12071.html

Mission Directorate.[2] The Astrobiology Program has six elements: the NASA Astrobiology Institute, Exobiology and Evolutionary Biology, Planetary Science and Technology Through Analog Research, MatiSSE,[3] PICASO,[4] and the Habitable Worlds Program.

Recently, Dr. Ellen Stofan, NASA Chief Scientist, predicted that evidence of life will be found relatively soon – "I believe we are going to have strong indications of life beyond Earth in the next decade and definitive evidence within the next 20 to 30 years."[5]

Searching for Life within our Solar System

Extremophiles and Terrestrial Analogues

One aspect of astrobiology research which can be conducted without the considerable expense associated with space missions is the analysis of extremophiles (organisms that thrive in physically or geochemically extreme conditions that are detrimental to most life on Earth) and other potential terrestrial analogues to extraterrestrial forms of life.[6] Both macroscopic and microscopic analogues are investigated. By learning what sort of environmental 'fingerprints' terrestrial extremophiles leave, a wider search can be performed for potential life elsewhere. For example, to aid the search for life on Mars or Europa (one of the moons of the planet Jupiter with liquid water), the Mojave Desert was used as an analogue for its similar geological profile and (relatively) unshielded environment, in terms of solar radiation. The desert is home to a few varieties of hypoliths – organisms which survive by using semi-translucent rocks to trap moisture and to shield a portion of incoming ultraviolet radiation. Studies of these hypoliths have shown them to be versatile, able to inhabit quartz, carbonate, and talc, despite the different spectrum of light available after the filtering through material strata.[7] If such organisms as hypoliths developed on the planet Mars, they may have been able to adapt sufficiently to survive the higher radiation environment on Mars than is found on Earth.

Mars Exploration Program

NASA's Mars Exploration Program seeks to understand whether Mars was, is, or can be, a habitable world.[8] To discover the possibilities for past or present life on Mars, NASA's Mars Exploration Program is currently following an exploration strategy known as "Seek Signs of

---

[2] NASA Astrobiology Program at http://astrobiology.nasa.gov/
[3] Maturation of Instruments for Solar System Exploration
[4] Pathfinder Instruments for Cloud and Aerosol Spaceborne Observations
[5] Abby Phillip, "Why NASA's top scientist is sure that we'll find signs of alien life in the next decade" *Washington Post* (April 8th, 2015), at http://www.washingtonpost.com/news/speaking-of-science/wp/2015/04/08/why-nasas-top-scientist-is-sure-that-well-find-signs-of-alien-life-in-the-next-decade/
[6] An extremophile is an organism adapted to unusual limits of one or more abiotic factors in the environment. Some of the extreme conditions are temperature, pH, high salinity, high levels of radiation and high pressure. The Encyclopedia of Earth at http://www.eoearth.org/view/article/160977/
[7] Heather D. Smith, Mickael Baqué, Andrew G. Duncan, Christopher R. Lloyd, Christopher P. McKay and Daniela Billi (2014). Comparative analysis of cyanobacteria inhabiting rocks with different light transmittance in the Mojave Desert: a Mars terrestrial analogue. International Journal of Astrobiology, 13, pp 271-277. doi:10.1017/S1473550414000056
[8] NASA Mars Exploration homepage at http://mars.nasa.gov/programmissions/science/

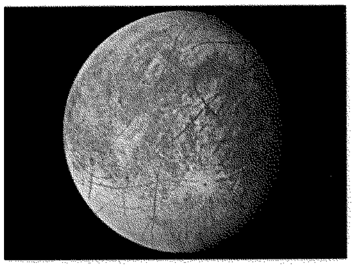
Life." This science theme is built on the prior science theme of "Follow the Water," which guided missions such as 2001 Mars Odyssey, Mars Exploration Rovers, Mars Reconnaissance Orbiter, and the Mars Phoenix Lander. The Mars Science Laboratory mission and its Curiosity rover mark a transition between the themes of "Follow the Water" and "Seek Signs of Life." In addition to landing in a place with past evidence of water, Curiosity is seeking evidence of organics, the chemical building blocks of life.

Curiosity looks for chemical elements that are the building blocks of life. These building blocks include six elements necessary to all life on Earth: carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur. In the past year, Curiosity made several major scientific discoveries relevant to the search for life, including measuring a spike in levels of the organic chemical methane in the local atmosphere of its research site and detecting other organic molecules in drill samples from a mudstone that once sat at the bottom of the lake that filled Gale Crater in Mars' ancient past.[9] Methane is important because it is an organic molecule often produced by life on Earth, although it can also be produced by different processes that do not involve living organisms. Curiosity provided the first definitive detection of organic molecules on the Martian surface when soil samples from the mudstone were analyzed. These samples also contained water.[10]

The follow-on to Curiosity is the 2020 Mars Rover mission. Mars 2020 will carry out in-situ exploration operations, including evaluations of habitability, preservation potential, and the presence of potential biosignatures within accessible geological materials. It will also collect samples of Martian material and seal them in individual tubes for possible return to Earth for more detailed analysis.

[9] P.R. Mahaffy, et al., "The Imprint of Atmospheric Evolution in the D/H of Hesperian clay minerals on Mars," *Science* Vol. 347 (January 23rd, 2015)
[10] Miriam Kramer, "Curiosity Rover Drills Into Mars Rock, Finds Water," Space.com (December 16th, 2014) at http://www.space.com/28030-mars-water-curiosity-rover.html

Europa Mission



Within our solar system, Jupiter's moon Europa is a leading candidate as a habitable environment which may include evidence of life.[11] For over 15 years NASA has developed concepts to explore Europa and determine if it is habitable based on characteristics of its vast oceans (twice the size of all of Earth's oceans combined), the ice surface–ocean interface, the chemical composition of the intriguing, irregular brown surface areas, and geologic activity providing energy to its system. For fiscal year 2015, NASA was appropriated $100 million for pre-formulation and formulation activities for a mission that meets the science goals outlined for the Jupiter Europa mission in the 2013 Planetary Science Decadal Survey.[12]

The instrumentation for the Europa mission was selected last month, and includes a mapping spectrometer, a magnetic sounding apparatus, and a dust analyzer.[13] Thermal, optical, and ultraviolet imaging systems are planned as well. Furthermore, potential landing probes such as the VALKYRIE (Very-deep Autonomous Laser-powered Kilowatt-class Yo-yoing Robotic Ice Explorer) continue to be investigated. VALKYRIE makes use of developing technologies in order to function on an extraterrestrial mission, including a laser power source and a minimally-contaminating design. It will be tested in the near future on frozen lakes and glaciers in Canada and Norway.[14]

Moons of Saturn

Two of Saturn's moons (Enceladus and Titan) are now believed to possess subsurface oceans, making them very attractive candidates for habitable environments within our planetary neighborhood. On Enceladus, recent analysis of the particulate matter ejected from plumes of water indicate hydrothermal processes in excess of 90 degrees centigrade occurring beneath the ice of the moon.[15] Titan has evidence of both subsurface oceans and stable bodies of surface liquid hypothesized to be hydrocarbon lakes.[16]

Habitable Exoplanets Around Other Stars

[11] Europa Study Team, "Investigating Icy World Habitability Through the Europa Clipper Mission Concept" Workshop on Habitabiolity of Icy Worlds, held February 5th – 7th, 2-14, in Pasadena, California at http://www.hou.usra.edu/meetings/icyworlds2014/pdf/4012.pdf
[12] P.L. 112-235
[13] NASA JPL Press Release, "NASA's Europa Mission Begin with Selection of Science Instruments" (May 26th, 2015)
[14] NASA Astrobiology Science Homepage at https://astrobiology.nasa.gov/astep/projects/nra/nnh11zda001n-astep/valkyrie-phase-2/
[15] Hsu, Postberg, et al., *Ongoing Hydrothermal Activities within Enceladus*, Nature 519, 207–210 (March 12th, 2015)
[16] J. Kawai, S. Jagota, et al., *Titan Tholins as Amino Acid Precursors and their Solubility in Possible Titan Liquidispheres,* Chemistry Letters Vol. 42 (2013) No.6 , 633-635

An extrasolar planet, or "exoplanet," is a planet that orbits a star other than our own. Astrobiologists and astrophysicists work together to discover and categorize exoplanets. Once such a planet is detected, the scientific challenge is to determine how to recognize – across the vast distance of interstellar space – whether that planet could (or does) support life.

The characterization of exoplanets and the identification of exoplanet biosignatures are supported through the science of atmospheric spectroscopy. Due to fortunate chance alignments of their orbits with our line of sight, some exoplanets alternatively pass in front of and behind their parent star as seen from Earth, providing a unique opportunity to analyze the atmospheres of these distant worlds. This is possible by observing the exoplanet and its parent star during a primary (or secondary) transit, when the planet passes in front of (or behind) the star. The planet's atmospheric constituents can be revealed by analyzing the characteristic absorption lines they imprint in the spectrum of the star when the star's light passes through the planet's atmosphere during a primary transit. Secondary transits provide an alternative method. Just before or after a secondary transit, the combined light from the star and exoplanet is seen. When the planet is entirely behind the star's disk, only the light from the star is seen. Taking the difference of these two signals reveals the spectrum of the exoplanet alone, which can be analyzed to identify the composition of the planet's atmosphere.

As the search for exoplanets continues, findings have exceeded expectations. As of September 10, 2015, there are 1,890 confirmed exoplanets, of which 31 meet the qualifications to be considered potentially Earth-like and habitable (i.e. within the circumstellar habitable zone with conditions roughly comparable to Earth) and many more could be home to new forms of life. [17,18] In light of the discoveries, it is now estimated that over 90 percent of stars in our galaxy have at least one planetary body, and that more than 70,000 exoplanets are likely to be identified by current missions within the next ten years.[19]

NASA-sponsored telescopes involved in exoplanet research include the Kepler Spacecraft Observatory, Large Binocular Telescope Interferometer (LBTI), the Hubble Space Telescope, the Spitzer Telescope, and the Stratospheric Observatory for Infrared Astronomy (SOFIA). Exoplanet research will also be conducted by the James Webb Space Telescope (JWST), the newly announced Explorer mission Transiting Exoplanet Survey Satellite (TESS), and potentially the Wide Field Infrared Survey Telescope (WFIRST).

Search for Extraterrestrial Intelligence (SETI)

In 1993, Congress cancelled funding to NASA's SETI program and NASA has not had a SETI program since.[20] However, there are a number of SETI research programs underway in the United States funded by organizations other than NASA, with most gathering under the aegis of the non-profit SETI Institute. These researchers conduct experiments searching for electromagnetic signatures in wavelengths from radio to visible light.

---

[17] NASA Exoplanet Science Institute at http://exoplanetarchive.ipac.caltech.edu/
[18] Planetary Habitability Laboratory at http://phl.upr.edu/projects/habitable-exoplanets-catalog/results
[19] M. Perryman, J. Hartman, et al., "Atmospheric Exoplanet Detection with Gaia" *The Astrophysics Journal* (November 19th, 2014).
[20] NASA History Program Office at http://history.nasa.gov/garber.pdf

On July 20, 2015, Yuri Milner and Stephen Hawking announced an unprecedented $100 million global Breakthrough Listen Initiative to support the search for intelligent life beyond Earth.[21] This 10 year program will include a survey of the 1,000,000 closest stars to Earth, scanning the center of our galaxy, the entire galactic plane, and also listen for messages from the closest 100 galaxies. This will be the largest scientific search ever undertaken for signs of intelligence life, covering 10 times more sky than and 5 times more radio spectrum than previous SETI programs.[22] All data will be made available to the public. This program will use the 100 meter Robert C. Byrd Green Bank Telescope in West Virginia, the Automated Planet Finder Telescope at Lick Observatory in California, and is in negotiations to use the Arecibo Telescope in Puerto Rico.

NASA Astrobiology Roadmap

Approximately every five years, NASA publishes an Astrobiology Roadmap which provides guidance for research and technology development across the NASA enterprises that encompass the space, Earth, and biological sciences. The Roadmap addresses three basic questions: how does life begin and evolve, does life exist elsewhere in the universe, and what is the future of life on Earth and beyond? The last roadmap was published in 2008.[23] The next roadmap was to be published in 2014. The new 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.

Nexus for Exoplanet System Science (NExSS)

The Nexus for Exoplanet System Science (NExSS) was announced last April.[24] NExSS is a NASA virtual institute designed to foster interdisciplinary collaboration in the search for life on exoplanets. Led by the Ames Research Center, the NASA Exoplanet Science Institute, and the Goddard Institute for Space Studies, and ten universities and two research NASA institutes, NExSS will help organize the search for life on exoplanets from participating research teams and acquire new knowledge about exoplanets and extrasolar planetary systems. The work of NExSS scientists will provide a foundation for interpreting observations of exoplanets from future exoplanet missions such as the Transiting Exoplanet Survey Satellite (TESS), the James Webb Space Telescope (JWST), and the Wide-field Infrared Survey Telescope (WFIRST).

---

[21] Breakthrough Initiatives Press Release "Yuri Milner and Stephen Hawking Announce $100 Million Breakthough Initiative to Dramatically Accelerate Search for Intelligent Life in the Universe" (July 20th, 2015)
[22] Id.
[23] Available at NASA Astrobiology Roadmap webpage, at https://astrobiology.nasa.gov/roadmap/
[24] NASA JPL Press Release, "NASA's NExSS Coalition to Lead Search for Life on Distinct Worlds" (April 21st, 2015)

Chairman SMITH. The Committee on Science, Space, and Technology will come to order. Without objection, the Chair is authorized to declare recesses of the Committee at any time.

Welcome to today's hearing, which is called "Astrobiology and the Search for Life beyond Earth in the Next Decade."

Let me make a couple of announcements. One is an explanation and that is to say that we expect more Members shortly, but at least on the Republican side, all of our Members are in a Republican conference that I left early in order to start on time here, but other Members will be arriving shortly. And the same may be true of our colleagues on the other side of the aisle as well.

We have a new member of the Science, Space, and Technology Committee, and I would like to introduce him. He is Darin LaHood, the first Member to my left, whose father I served with in Congress some years ago. Darin LaHood represents a district in Illinois. He's a former State Senator or serving as a State Senator when he was elected to Congress. Before that, he was both a State and Federal prosecutor. So we welcome his many talents to the Committee. He is going to be serving on two subcommittees, Research and Technology and Oversight, where he will be bringing all those legal skills to bear. And so we are pleased to have him join us today and permanently on this Committee. Welcome, Darin, to you.

Mr. LAHOOD. Thank you, Mr. Chairman.

Chairman SMITH. I'm going to recognize myself for an opening statement and then I'll recognize the Ranking Member.

Edwin Hubble once said: "Equipped with his five senses, man explores the universe around him and calls the adventure Science." There are few greater adventures than the search for life beyond Earth.

When the Hubble Space Telescope was launched in 1990, planets around other stars had not yet been discovered. The only planets we knew were those that orbited our Sun. Since 1995, however, when the first extrasolar planet was detected, the rate of discovery of new exoplanets and external solar systems has been truly remarkable.

Today, with the Kepler Telescope, we have found nearly 2,000 confirmed planets that orbit around other stars in our galaxy. Of these, 306 lie within the habitable zone of the stars they orbit—where water could exist—and 14 are almost the size of the Earth.

Whether life exists beyond Earth, and if so, how humans can detect it, is a critical question. If definitive evidence of life is found, it may be the most significant scientific discovery in human history. The search for life in the universe is a priority of NASA and the U.S. scientific community. Seeking habitable planets is one of the three scientific objectives of the 2010 National Research Council Decadal Survey on astronomy and astrophysics.

The United States pioneered the field of astrobiology and continues to lead the world in this type of research. Since the space program began, NASA has explored the cosmos for life beyond Earth and has conducted scientific research that investigates this possibility.

NASA's astrobiology program continues these scientific endeavors to improve our understanding of biological, planetary, and cosmic phenomena. Just yesterday, NASA announced that it identified flowing briny water on Mars. This past April, NASA's Chief Scientist, Dr. Ellen Stofan, made global headlines with her prediction that "we are going to have strong indications of life beyond Earth in the next decade and definitive evidence within the next 20 to 30 years." And I am glad that Dr. Stofan has joined us today.

Within our solar system, the question of whether life exists or existed on Mars continues to capture the public imagination. In the past year, NASA's Curiosity Rover made several major scientific discoveries relevant to the search for life on Mars. Curiosity measured a spike in levels of the organic chemical methane in the local atmosphere of its research site. It also detected other organic molecules in drill samples in a mudstone that once sat at the bottom of a lake. And Jupiter's moon, Europa, shows strong evidence of an ocean of liquid water beneath its surface, which could host conditions favorable to some form of life.

NASA selected nine science instruments for a future mission to Europa. Two of them are from the Southwest Research Institute in San Antonio and one from the University of Texas in Austin. These instruments will help scientists investigate the chemical makeup of Europa's potentially habitable environment.

Last July, astronomers, with the help of the Kepler Space Telescope, confirmed the discovery of Kepler 452-b, the first near-Earth-size planet in the "habitable zone" around a sun-like star. This discovery marks another milestone in the journey to find another "Earth."

The Transiting Exoplanet Survey Satellite, which will launch in 2017, and the James Webb Space Telescope, which will begin in 2018, will help scientists discover more planets with potential biosignatures in their atmospheres, such as evidence of oxygen and methane gas. Around the world a relatively small number of astronomers monitor radio and optical emissions throughout the universe. They try to filter out the cosmic noise and interference of satellites and spacecraft to find anomalies that could represent life.

The search for life beyond Earth also inspires a new generation of explorers. It motivates students to study math, science, engineering, and computer science. Just a few months ago, astronomers confirmed that Tom Wagg, a 15-year-old student, discovered exoplanet WASP–142b, which orbits a star approximately 1,000 light years away in the constellation Hydra.

It is in our human nature to seek out the unknown and to discover the universe around us. The stars compel us to look upward and lead us from this world to another. Many Americans often gaze into the beauty of the night sky in awe; some may wonder if there is life beyond our pale blue dot.

I thank our witnesses and look forward to hearing their testimony and particularly about recent developments in the field of astrobiology and the search for life.

[The prepared statement of Chairman Smith follows:]

PREPARED STATEMENT OF COMMITTEE CHAIRMAN LAMAR S. SMITH

Edwin Hubble once said: "Equipped with his five senses, man explores the universe around him and calls the adventure Science." There are few greater adventures than the search for life beyond Earth.

When the Hubble Space Telescope was launched in 1990, planets around other stars had not yet been discovered. The only planets we knew were those that orbited our Sun.

Since 1995, however, when the first extrasolar planet was detected, the rate of discovery of new exoplanets and external solar systems has been truly remarkable.

Today, with the Kepler Telescope, we have found nearly 2000 confirmed planets that orbit around other stars in our galaxy. Of these, 306 lie within the habitable zone of the stars they orbit-where water could exist-and 14 are almost the size of Earth.

Whether life exists beyond Earth, and if so, how humans can detect it, is a critical question. If definitive evidence of life is found, it may be the most significant scientific discovery in human history.

The search for life in the Universe is a priority of NASA and the U.S. scientific community. Seeking habitable planets is one of the three scientific objectives of the 2010 National Research Council decadal survey on astronomy and astrophysics.

The United States pioneered the field of astrobiology and continues to lead the world in this type of research. Since the space program began, NASA has explored the cosmos for life beyond Earth and has conducted scientific research that investigates this possibility.

NASA's astrobiology program continues these scientific endeavors to improve our understanding of biological, planetary, and cosmic phenomena. Just yesterday, NASA announced that it identified flowing briny water on Mars.

This past April, NASA's Chief Scientist, Dr. Ellen Stofan, made global headlines with her prediction that "we are going to have strong indications of life beyond Earth in the next decade and definitive evidence within the next 20 to 30 years." I am glad Dr. Stofan has joined us today.

Within our solar system, the question of whether life exists or existed on Mars continues to capture the public imagination.In the past year, NASA's Curiosity Rover made several major scientific discoveries relevant to the search for life on Mars.

Curiosity measured a spike in levels of the organic chemical methane in the local atmosphere of its research site. It also detected other organic molecules in drill samples from a mudstone that once sat at the bottom of a lake.

And Jupiter's moon, Europa, shows strong evidence of an ocean of liquid water beneath its surface, which could host conditions favorable to some form of life.

These instruments will help scientists investigate the chemical makeup of Europa's potentially habitable environment.

Last July, astronomers, with the help of the Kepler Space Telescope, confirmed the discovery of Kepler 452-b, the first near-Earth-size planet in the "habitable zone" around a sun-like star. This discovery marks another milestone in the journey to find another "Earth."

The Transiting Exoplanet Survey Satellite, which will launch in 2017, and the James Webb Space Telescope, which will begin in 2018, will help scientists discover more planets with potential biosignatures in their atmospheres—such as evidence of oxygen and methane gas.

Around the world a relatively small number of astronomers monitor radio and optical emissions throughout the universe. They try to filter out the cosmic noise and interference of satellites and spacecraft to find anomalies that could represent life.

The search for life beyond Earth also inspires a new generation of explorers. It motivates students to study math, science, engineering, and computer science.

Just a few months ago, astronomers confirmed that Tom Wagg, a 15 year old student, discovered exoplanet WASP-142b, which orbits a star approximately 1,000 light years away in the constellation Hydra.

It is in our human nature to seek out the unknown and to discover the universe around us. The stars compel us to look upward and lead us from this world to another. Many Americans often gaze into the beauty of the night sky in awe, some may wonder if there is life beyond our pale blue dot.

I thank our witnesses and look forward to hearing their testimony and particularly about recent developments in the field of astrobiology and the search for life.

Chairman SMITH. And now I will recognize the gentlewoman from Texas, Eddie Bernice Johnson, the Ranking Member, for her opening statement.

Ms. JOHNSON OF TEXAS. Thank you very much, Mr. Chairman, and good morning. Let me welcome our distinguished panel of witnesses today. I do look forward to your testimony.

I want to welcome Mr. LaHood to the Committee and simply say that the first week of this month I visited the Curiosity team in France, and the excitement is beyond measure.

Administrator Bolden stated in the preface of NASA's Strategic Plan that "when we explore the solar system and the universe, we gain knowledge about the dynamics of the Sun and the planetary system and whether we are alone."

With respect to the question of whether we are alone, the search for life beyond Earth is a topic this Committee has devoted a lot of attention to over the past two years. I don't know if we plan on taking up life somewhere else. I don't know where our Chairman wants to go, but I'm interested in following him.

I understand that the purpose of today's hearing is to get another update on that topic. It is my hope that our witnesses will also take some time to discuss how their research activities can be used to help foster excitement in our young people and spur them to pursue careers in science, technology, engineering, and math. That's important because these young people are the future science and technological leaders and innovators who will be critical to our nation's growth and progress going forward. While it's exciting to search for intelligent life elsewhere in the universe, I hope we don't neglect nurturing the intelligent life we have right here in our country.

As a final note, I want to recognize that this is a return visit by Dr. Lunine. One year ago he and Governor Mitch Daniels testified before the Committee on their National Research Council panel's report entitled "Pathways to Exploration: A Review of the Future of Human Space Exploration." And that was completed pursuant to the NASA Authorization Act of 2010. I highly recommend that our newer colleagues on the Committee and in the rest of the Congress as a whole for that matter read this report, as I found it to be objective in its endorsement of the goal of sending humans to Mars and thoughtful in its recommendations for an exploration program to send humans to the surface of Mars, a central goal established by this Committee in the House-passed NASA Authorization Act of 2015.

And with that, I again want to thank our witnesses and I yield back. Thank you.

[The prepared statement of Ms. Johnson of Texas follows:]

PREPARED STATEMENT OF COMMITTEE RANKING MEMBER
EDDIE BERNICE JOHNSON

Good morning and welcome to our distinguished panel of witnesses. I look forward to your testimony.

Administrator Bolden stated, in the preface of NASA's Strategic Plan, that when we explore the solar system and the universe, we gain knowledge about the dynamics of the Sun and the planetary system and whether we are alone.

With respect to the question of whether we are alone, the Search for Life Beyond Earth is a topic this Committee has devoted a lot of attention to over the past two years. I understand that the purpose of today's hearing is to get another update on that topic. It is my hope that our witnesses will also take some time to discuss how their research activities can be used to help foster excitement in our young people and spur them to pursue careers in Science, Technology, Engineering, and Mathematics.

That's important, because those young people are the future science and technological leaders and innovators who will be critical to our Nation's growth and progress going forward. While it's exciting to search for intelligent life elsewhere in the universe, I hope we don't neglect nurturing the intelligent life we have right here in this country now.

As a final note, I want to recognize that this is a return visit by Dr. Lunine. One year ago, he and Governor Mitch Daniels testified before this Committee on their National Research Council panel's report titled "Pathways to Exploration: A Review of the Future of Human Exploration" that was completed pursuant to the NASA Authorization Act of 2010.

I highly recommend that my newer colleagues on the Committee, and in the rest of the Congress as a whole for that matter, read this report as I found it to be objective in its endorsement of the goal of sending humans to Mars, and thoughtful in its recommendations for an exploration program to send humans to the surface of Mars—a central goal established by this Committee in the House-passed NASA Authorization Act of 2015.

With that, I again want to welcome our witnesses to today's hearing, and I yield back.

Chairman SMITH. I thank the Ranking Member for those nice comments.

Let me introduce our witnesses. Our first witness is Dr. Ellen Stofan, NASA's Chief Scientist. She serves as principal advisor to NASA Administrator Charles Bolden on the agency's science programs and science-related strategic planning and investments. This is Dr. Stofan's second term at NASA, as she recently held a number of senior scientist positions at the Jet Propulsion Laboratory. Dr. Stofan is the recipient of the Presidential Early Career Award for Scientists and Engineers. She earned her bachelor's degree from William and Mary and her master's and doctorate degrees in geological sciences from Brown University.

Our second witness today is Dr. Jonathan Lunine, the Director of the Cornell Center for Astrophysics and Planetary Science at Cornell University, where he specializes in astrobiology. Dr. Lunine has extensive experience in the search for life on other planets. He worked as an interdisciplinary scientist on the Cassini mission, which showed that one of Saturn's moons may host micro-bio life, and on the James Webb Space Telescope, which will study the origins of life in the near future. Dr. Lunine received his bachelor's degree in physics and astronomy from the University of Rochester and his master's and Ph.D. in planetary science from the California Institute of Technology.

Our third witness is Dr. Jacob Bean, Assistant Professor of Astronomy and Astrophysics at the University Of Chicago. Dr. Bean also is the leader of the Bean Exoplanet Group, which uses telescopes to detect and characterize exoplanets. Dr. Bean's work has used the Hubble and Spitzer telescopes to make breakthroughs in astrobiology, which include the measurement of the first spectrum of a super-Earth planet. Dr. Bean also develops new instruments for exoplanet detection and characterization and is helping to design the giant Magellan telescope, which will soon be the world's largest telescope. Dr. Bean received his undergraduate degree in physics from the Georgia Institute of Technology and his Ph.D. in astronomy from the University of Texas in Austin.

Our final witness today is Dr. Andrew Siemion. Dr. Siemion is an astrophysicist at the University of California Berkeley and served as Director of the U.C. Berkeley Center for Search for Extraterrestrial Intelligence Research. Dr. Siemion's research interests include studies of time variable celestial phenomena, astronomical instrumentation and SETI, and Dr. Siemion also is a leader of the Breakthrough Listen Initiative, a ten-year, $100 million initiative to search for extraterrestrial life that is possibly the most comprehensive search for alien communications to date. Dr. Siemion received his Ph.D. in astrophysics from the University of California at Berkeley.

We welcome you all. You're clearly experts in the field. And, Dr. Stofan, you begin.

TESTIMONY OF DR. ELLEN STOFAN, CHIEF SCIENTIST, NASA

Dr. STOFAN. Thank you. I'm pleased to appear before the Committee to discuss astrobiology and the search for life beyond Earth. If I could have the first slide, please.

[Slide.]

NASA's science missions are providing strong evidence of possible habitable environments beyond Earth. With future technology and instruments currently under development, we will explore the solar system and beyond, and could indeed, perhaps in as little as 10 to 20 years, discover some form of life, past or present.

Our search is making amazing progress. When I was a Ph.D. student, scientists certainly suspected that planets might be commonplace in the universe, but we have not found evidence of a single one. Twenty years ago, we found evidence of such a planet, and today, thanks to NASA's space missions and ground-based telescopes, we have identified nearly 5,000 planets orbiting other stars, and we now believe that that the vast majority of stars in the universe have planets around them. In July, the Kepler mission confirmed the first near-Earth-size planet in the "habitable zone" around a sun-like star, Kepler-452b.

On Mars, a series of NASA missions culminating in the Curiosity Rover, which touched down in Gale Crater nearly three years ago, have allowed us to make fundamental discoveries. Next slide.

[Slide.]

We now know that Mars was once a water world much like Earth, with clouds and a water cycle, and indeed some running water currently on the surface. For hundreds of millions of years, about half of the northern hemisphere of Mars had an ocean, possibly a mile deep in places.

Indeed, we now know that we live in a soggy solar system, and undoubtedly, in a soggy universe. For instance, Jupiter lies outside the habitable zone and we would expect water there to be frozen. Yet we now have evidence of liquid oceans on three moons of Jupiter under the icy crusts of those worlds. And using the Hubble and Spitzer Space Telescopes, we have found signs of water in the atmospheres of planets around other stars.

So what lies ahead in the next decade of exploration? I'd like to describe just some of the highlights. Life as we know it requires water, liquid water, that's been stable on the surface of a planet for a very long time. That's why Mars is our primary destination in the search for life in our solar system. The Mars 2020 Rover mission will study Martian rocks and soils to understand past habitable conditions on Mars and to seek signs of ancient microbial life. If we do find evidence of life on Mars, it will likely be fossilized microorganisms preserved in the rock layers. The Mars 2020 Rover will begin the search, but as a field geologist, I can tell you it's going to be hard to find. That's why I believe it will take human explorers who can move quickly and make intuitive decisions on their feet to really identify it, and in doing so, inspire that next generation of explorers.

Over the next decade, our journey to Mars involves the development of a commercial crew capability for low-Earth orbit, the Space Launch System and Orion, to go beyond low-Earth orbit and an asteroid redirect mission.

Beyond Mars, the President's fiscal year 2016 budget request supports the formulation and development of a new mission to the Jovian moon Europa. If I could have the next slide.

[Slide.]

We estimate that Europa has twice as much water as the Earth's oceans, and Hubble has observed plumes of water at one of Europa's poles. A Europa mission could potentially, among other things, analyze these water plumes to determine the composition of those oceans.

Beyond our solar system, there are countless other worlds that could harbor life. In 2017, NASA will launch the Transiting Exoplanet Survey Satellite to look for rocky planets near the habitable zone of the closest stars. Next slide.

[Slide.]

We will then use the James Webb Space Telescope to analyze the atmospheres of some of these planets. The President's fiscal year 2016 budget request also supports the pre-formulation of a Wide Field Infrared Survey Telescope with the capability of directly imaging planets around the nearest stars and analyzing their atmospheres.

Since Earth remains, for now, the only instance of an inhabited planet, the search for life also requires that we further develop our understanding of life on Earth. Through our research here, we have learned that life is tough, tenacious, metabolically diverse, and highly adaptable to local environmental conditions. Astrobiologists have discovered life in numerous extreme environments and in extraordinary forms from bacteria that consume chemicals that would be toxic to most other life, to microbes that live under high levels of radiation.

Perhaps even more interesting is the possibility that life could exist in the absence of liquid water. That's why scientists are interested in exploring some of the more unusual places in our solar system and beyond, such as Saturn's moon Titan, where it rains liquid methane and ethane. Could such an environment harbor life? We don't know yet.

Ultimately, of course, the search for life is a crosscutting theme in all of NASA's space science endeavors, bringing together research in astrophysics, Earth science, heliophysics, and planetary science. Astrobiology is guided by a community-constructed roadmap generated about every five years with the next roadmap slated for release later this year.

In addition, in April NASA announced the formation of an initiative dedicated to the search for life on planets outside our solar system. The Nexus for Exoplanet System Science is an interdisciplinary effort that connects top research teams and provides a synthesized approach in the search for planets with the greatest potential for harboring life.

From research, to our knowledge of where to go and what to look for, to the capabilities of finding it both within our solar system and beyond, we are making great discoveries.

Thank you for the opportunity to testify today.

[The prepared statement of Dr. Stofan follows:]

HOLD FOR RELEASE
UNTIL PRESENTED
BY WITNESS
September 29, 2015

Statement of

Dr. Ellen Stofan
Chief Scientist
National Aeronautics and Space Administration

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

Chairman Smith, Ranking Member Johnson and Members of the Committee,
I am pleased to have the opportunity to appear before you to discuss astrobiology and the search for life beyond Earth.

NASA's robotic spacecraft and telescopes are providing strong evidence of possible habitable environments beyond Earth. With future technology and instruments currently under development, we will explore the solar system and beyond, and could indeed -- perhaps in as little as 10-20 years -- discover some form of life, past or present.

Our search is making amazing progress. When I was a PhD student, scientists certainly suspected that planets must be commonplace in the Universe, but we had not found evidence of a single one. Twenty years ago, we found evidence of the first such planet. Today, thanks to NASA's Kepler, Hubble, and Spitzer space missions and several ground-based telescopes, we have identified nearly 5,000 planets orbiting other stars – and we now believe that that the vast majority of stars in the Universe have planets. In July, the Kepler mission confirmed the first near-Earth-size planet in the "habitable zone" around a sun-like star. Kepler-452b is the smallest planet to date discovered orbiting in the habitable zone of a star like our sun.

On Mars, a series of NASA missions culminating in the *Curiosity* rover, which touched down in Gale Crater nearly three years ago, have allowed us to make amazing discoveries. We now know that Mars was once a water world much like Earth, with clouds and a water cycle. For hundreds of millions of years, about half of the northern hemisphere of Mars had an ocean, possibly a mile deep in some places. *Curiosity* is now at the edge of where that ocean was and *Curiosity* has determined that the Martian soil is currently about 2 percent water, by weight.

Indeed, we now know that we live in a soggy solar system, and undoubtedly, in a soggy universe. We continue to find vast amounts of liquid water in unlikely places. For instance, Jupiter lies outside the habitable zone and we would expect water in Jupiter's vicinity to be frozen. Yet we now have evidence of liquid oceans on three of the four moons of Jupiter, sloshing around tantalizingly under the icy crusts of those worlds. Using the Hubble and Spitzer space telescopes, we have found signs of water in the atmospheres of planets around other stars.

So what lies ahead in the next decade of exploration? I would like to describe just some of the highlights.

Life - as we know it - requires water, specifically liquid water, that has been stable on the surface of a planet for a very long time. That's why Mars is our primary destination in the search for life in our solar system, because our robotic spacecraft have shown us strong evidence that water was stable on Mars for a very long time.

In July 2014, NASA selected the instruments for the Mars 2020 rover mission, which will study Martian rocks and soils to understand past habitable conditions on Mars and to seek signs of ancient microbial life. Mars 2020 will also test our ability to extract oxygen from the Red Planet's carbon-dioxide atmosphere to prepare for future human exploration.

If we do find evidence of life on Mars, it will likely be fossilized microorganisms preserved in the rock layers. The Mars 2020 rover will begin the search, but as a field geologist, I can tell you it may be hard to find. That's why I believe it will take human explorers - geologists and astrobiologists - who can move quickly and make intuitive decisions on their feet - to identify it.

Over the next decade, our journey to Mars involves the development of a commercial crew capability for low earth orbit, the development of the Space Launch System (SLS) and *Orion* to go beyond low earth orbit, and the proving ground of an asteroid redirect mission. We are well on our journey, with a very successful first flight test of *Orion* this past December and hardware for the first SLS well underway.

Beyond Mars, we are planning to look at another intriguing world in our solar system. The President's Fiscal Year (FY) 2016 budget request supports the formulation and development of a mission to the Jovian moon Europa. We estimate that Europa has twice as much water as the Earth's oceans and that there is an interchange of materials between Europa's icy crust and its water oceans. *Hubble* has observed plumes at one of Europa's poles. A Europa mission could potentially, among other things, analyze Europa's water plumes to determine the composition of those oceans.

Of course, beyond our solar system, there are countless other worlds that could harbor life. As I mentioned above, space- and ground-based telescopes have found nearly 5,000 exoplanets to date. The majority of these exoplanets are giant gas planets close to their home stars, because such planets are more easily detected. However, extrapolating from the available data, we calculate that the majority of the planets in the Universe are smaller rocky planets, which are more likely to support life. In 2017, NASA will be launching the Transiting Exoplanet Survey Satellite, (TESS), which will look for rocky planets near the habitable zones of the closest stars. With TESS' planets in hand, we will use the James Webb Space Telescope to analyze the kinds of molecules that such planets' atmospheres contain, such as water, oxygen, carbon dioxide and methane. The President's FY 2016 budget request supports the pre-formulation of a Wide Field Infrared Survey Telescope with the capability of directly imaging planets around the nearest stars and analyzing their atmospheres. These will be the prime targets for our search for life.

Since Earth remains – for now – the only known instance of an inhabited planet, the search for life in the cosmos also requires that we further develop our understanding of life on Earth. Through our research on Earth, we have learned that life is tough, tenacious, metabolically diverse and highly adaptable to local environmental conditions. Astrobiologists have discovered life in numerous extreme environments on Earth such as volcanic lakes, glaciers, sulfur springs and the top of the stratosphere. We have also found life in extraordinary forms, ranging from bacteria that consume chemicals that would be toxic to most other life, to microbes that live under high levels of gamma or ultraviolet radiation.

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 an atmospheric pressure, equivalent to that of Mars, which is less than one percent of Earth's average pressure. 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 could survive and even reproduce under these extreme conditions.

Perhaps even more interesting is the possibility that life could exist in the absence of liquid water. That's why scientists are interested in exploring some of the more unusual places in our solar system and beyond, such as Saturn's moon Titan, where it rains liquid methane and ethane. Could such an environment harbor life? We don't know yet.

Ultimately, of course, the search for life is a crosscutting theme in all of NASA's space science endeavors, bringing together research in astrophysics, Earth science, heliophysics and planetary science. Astrobiology is guided by a community-constructed roadmap generated about every five years, most recently in 2008, with the next roadmap slated for release this year. 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.

In addition, in April NASA announced the formation of an initiative dedicated to the search for life on planets outside our solar system. The Nexus for Exoplanet System Science is an interdisciplinary effort that connects top research teams and provides a synthesized approach in the search for planets with the greatest potential for signs of life. All of the research teams participating in this network are funded by grants from the four research divisions of NASA's Science Mission Directorate. Those grants were awarded through NASA's standard competitive solicitation, peer review and selection process. This new network will help scientists communicate and coordinate their research, training and educational activities across disciplinary, organizational, divisional and geographic boundaries. It will also foster new collaborations, including international partnerships, address interdisciplinary topics, and help break down barriers between stove-piped research activities.

From research, to our knowledge of where to go and what to look for, to the capabilities of finding it both within our solar system and beyond, we are making great discoveries.

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

Dr. Ellen Stofan

Dr. Ellen Stofan was appointed NASA chief scientist on August 25, 2013, serving as principal advisor to NASA Administrator Charles Bolden on the agency's science programs and science-related strategic planning and investments.

Prior to her appointment, Stofan was vice president of Proxemy Research in Laytonsville, Md., and honorary professor in the department of Earth sciences at University College London in England. Her research has focused on the geology of Venus, Mars, Saturn's moon Titan, and Earth. Stofan is an associate member of the Cassini Mission to Saturn Radar Team and a co-investigator on the Mars Express Mission's MARSIS sounder. She also was principal investigator on the Titan Mare Explorer, a proposed mission to send a floating lander to a sea on Titan.

Her appointment as chief scientist marks a return to NASA for Dr. Stofan. From 1991 through 2000, she held a number of senior scientist positions at NASA's Jet Propulsion Laboratory in Pasadena, Calif., including chief scientist for NASA's New Millennium Program, deputy project scientist for the Magellan Mission to Venus, and experiment scientist for SIR-C, an instrument that provided radar images of Earth on two shuttle flights in 1994.

Stofan holds master and doctorate degrees in geological sciences from Brown University in Providence, R.I., and a bachelor's degree from the College of William and Mary in Williamsburg, Va. She has received many awards and honors, including the Presidential Early Career Award for Scientists and Engineers. Stofan has authored and published numerous professional papers, books and book chapters, and has chaired committees including the National Research Council Inner Planets Panel for the recent Planetary Science Decadal Survey and the Venus Exploration Analysis Group.

Chairman SMITH. Thank you, Dr. Stofan.
Dr. Lunine.

TESTIMONY OF DR. JONATHAN LUNINE, DAVID D. DUNCAN PROFESSOR IN THE PHYSICAL SCIENCES, AND DIRECTOR, CENTER FOR RADIOPHYSICS AND SPACE RESEARCH, CORNELL UNIVERSITY

Dr. LUNINE. Thank you, Chairman Smith, Ranking Member Johnson, and members of the committee. Thank you for the opportunity to present my views on the search for life beyond Earth. These views are my own and they come from 30 years of working in the field of planetary science at various institutions in the United States and abroad.

One of the most important outcomes of the last two decades of solar system exploration is the identification of four bodies in our solar system that appear capable of harboring life. These bodies possess a particular set of characteristics that make them the best leads in the search for life beyond the Earth. And if I could have the first slide, the first of these bodies is Mars.

[Slide.]

In its first billion years, Mars had abundant liquid water, stabilized and protected by a much denser atmosphere than the tenuous shell we see today. During this time, life might have begun, survived for a while on the surface, and then was extinguished or retreated underground as the atmosphere was lost. If I could have the second slide——

[Slide.]

The second of these objects is Jupiter's moon Europa. It's a body the size of our own moon. It has a very large saltwater ocean, twice the water that we have in our own ocean. This ocean is in contact with a rocky core and abundant sources of energy. As yet, we don't know whether organic molecules exist inside of this ocean, but we strongly suspect that they are there. Equally important, we don't know how far beneath Europa's surface the ocean lies. Knowing that will allow a strategy to be formulated for searching for life there.

[Slide.

Next slide is Titan, a Saturnian moon that's larger than the planet Mercury and the only moon in our solar system to host a dense atmosphere of nitrogen and methane. Cassini and its lander Huygens have revealed methane clouds, rain, gullies, river valleys, and methane/ethane seas, and so we cannot resist asking whether some biochemically novel form of life might have arisen in this exotic frigid environment. Titan is a test for the universality of life as an outcome of cosmic evolution. To quote the historian Stephen Pyne, "What the Galapagos Islands did for the theory of evolution by natural selection, Titan might do for exobiology."

[Slide.]

Finally, next slide, Enceladus has surprised us. This small Saturnian moon has a large plume of material emanating from a series of fractures in its south polar region. Make a list of requirements for terrestrial-type life—liquid water, organics, minerals, energy, chemical gradients—and Cassini has found evidence for all of them in the plum of Enceladus.

So how do we actually find the signs of life in these bodies? The evidence will not be entire living organisms. Much more likely is that we will detect signatures that indicate that life is at work or was at work in these environments. In contrast to nonbiological processes, biology is built from a very limited, selected set of molecules, and so if we can recognize patterns in the makeup of organic molecules and their isotopes, we then have strong evidence of biology at work.

At Mars, finding sources of methane and measuring their isotopes is one way to get at this question. Another is to seek well-preserved organic materials in the soil to see if they record the signatures of biology. And the Mars 2020 Rover will do the heavy lifting here.

For Europa, the Europa mission now in development will provide the essential information needed to decide, among other things, whether organics and water are welling up through the cracks on the surface and whether plumes exist and can be measured. Doing this mission, doing it now is absolutely crucial to any general strategy for the search for life.

For Titan, the search to target one of the great methane/ethane seas by dropping a capsule capable of floating across the surface. We don't know what kind of biochemistry we're looking for here and so a generalized search for patterns and molecular structures and abundances that indicate deviation from abiotic chemistry is appropriate.

And finally, Enceladus provides us with the most straightforward way to look for life. Merely flying through the plume of Enceladus, as Cassini has done multiple times, with modern instrumentation intended to detect the signatures of life, is sufficient to do the search.

The long flight times in the outer solar system in particular dictate the planning for missions to Enceladus, Europa, and Titan must begin now and must be pursued with vigor if they're to happen in the next two decades. It is remarkable that we have found four destinations in our own solar system where life may actually exist or have existed for quite some time in the past and now is the time to actually go search for the life.

Thank you.

[The prepared statement of Dr. Lunine follows:]

HOLD FOR RELEASE
UNTIL PRESENTED
BY WITNESS
September 29, 2015

Statement of

Dr. Jonathan I. Lunine

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

Chairman Smith, Ranking Member Johnson and Members of the Committee,
Thank you for the opportunity to present my views on astrobiology and the search for life beyond Earth. These views are my own and come from thirty years of working in the field of planetary science, at various institutions here in the US and abroad.

Two decades ago the discovery of the first planet around another sun-like star was announced. Were I to have testified then in this room on the subject of promising places to search for life in our own solar system, I would have said there were no obvious targets. In 1995 the US had yet to mount a successful Mars mission after the Viking landers and orbiters of the 1970's. The Galileo orbiter was enroute to Jupiter, but with prospects for successful mission marred by a crippled communications antenna. Cassini was more than two years away from launch and nine years from its target, Saturn. The exuberance of the first three decades of planetary exploration had faded and it was not clear what the coming years would bring.

But fast-forward ten years and one sees the exuberance returned. Europa had become a target of keen astrobiological interest after the Galileo orbiter found multiple lines of evidence for a subsurface ocean. Cassini, safely in Saturn orbit, dropped off the European Huygens probe for a successful landing on the giant moon Titan, and then discovered a huge plume of vapor and ice pouring out of the south polar region of Saturn's tiny moon Enceladus. The first geochemical evidence of standing liquid water on ancient Mars—the Mars of billions of years past—was found by a rover called Opportunity.

Fast-forward one more decade to the present-day, and we see the Cassini orbiter directly measuring water, salts and organics in Enceladus' plume. Cassini also is probing with radar the depths and composition of Titan's surface seas of liquid methane and ethane, seas it discovered in 2007. An SUV-sized rover called Curiosity is sniffing the Martian air and tasting the soil; it rolled across an ancient riverbed where water flowed billions of years ago, and is traveling toward Mt. Sharp where the sediments may record two billion years of Martian history. And just this month NASA selected instruments and brought into Phase-A a mission to Europa, a mission that will pave the way for the search for life there.

One of the major results of these last two decades of solar system exploration is the identification of four bodies that may well harbor, or have harbored, life. (By life I am referring to single-celled, microbial life; there is little expectation for anything more complex.) These four suspects possess a particular set of characteristics beyond liquid water that make them, in my view and that of many other scientists, the best leads in the search for life beyond Earth. Let me list for you the specific reasons why:

Mars (figure 1) is the most Earth-like planet in the solar system and has had a rich geological and atmospheric history. In its first billion years Mars had abundant surface liquid water, stabilized and protected by a much denser atmosphere than the tenuous shell of gas we see today. During this time life might have begun, survived for some time on the surface, and then either was extinguished or retreated underground as the atmosphere was lost. The burst of methane detected by the Curiosity rover is intriguing as a possible sign of life, but life is not the only generator of methane: even on the Earth, hot water and carbon dioxide in the presence of the right kind of rock can also make methane. It will require very sensitive measurements of carbon isotopes to determine the origin of the methane.

Europa (figure 2)—the lunar-sized moon of Jupiter-- has a very large salt-water ocean in contact with a rocky core, chemical energy gradients associated with Jupiter's radiation belts, and a prodigious energy budget from tidal heating-- but we know little else about the prospects for life here. Indeed, we do not know whether organic (carbon-hydrogen) molecules exist within the ocean—but we strongly suspect they are there. Equally important, we do not know how far beneath the moon's surface the ocean lies. Knowing that will allow a strategy to be formulated to search for life there.

Titan (figure 3) is larger than the planet Mercury and is the only moon to host a dense atmosphere of nitrogen and methane. The source of the methane—how it is sustained in the atmosphere over billions of years of destruction by ultraviolet rays from the Sun—remains a mystery. But Cassini and its lander Huygens have revealed a "hydrologic cycle" with clouds, rain, gulleys, river valleys and seas. Methane is the working fluid in place of water because the surface temperature is so low. The surface seas –concentrated in the arctic region of Titan--are so vast that they hold hundreds of times more hydrocarbons than do the known oil and gas reserves on planet Earth. And so we cannot avoid asking whether a form of life might have arisen in this exotic, frigid environment. Titan's surface has all the formal requirements for life—abundant organics, liquids, and sources of energy such as sunlight, wind, tides. And yet, that liquid is not water—it is methane. Should we include the seas of Titan in our search for life? As a 2007 National Research Council study[1] asserted: "if life is an intrinsic property of chemical reactivity, life should exist on Titan." Titan is a test for the universality of life as an outcome of cosmic evolution. To quote Stephen Pyne, "What the Galapagos Islands did for the theory of evolution by natural selection, Titan might do for exobiology"[2] It's a wild card, to be sure—but by playing that

[1] The Limits of Organic Life in Planetary Systems, National Research Council, National Academies Press, Washington DC, 2007, p. 74.
[2] Pyne, S. Exploration, Space and the Third Great Age of Discovery. Penguin, NY, 2010, p. 206.

card we give ourselves the chance of discovering something profoundly important about the way the universe works.

Enceladus (figure 4) has surprised us. This Saturnian moon is only one-thousandth the volume of neighboring Titan, and yet it sports a plume of material emanating from a series of fractures in its south polar region. Cassini has flown repeatedly through this expanding cloud of icy grains and vapor, and will do so again next October. Thanks to the prodigious capabilities of its chemical sniffers—mass spectrometers—and other instruments, Cassini has found organic molecules, frozen drops of salty water, and tiny grains of silica that hint at a hot hydrothermal system in a deep interior ocean from which the jets that source the plume presumably emanate. Cassini's sensitive measurements of the gravity field of Enceladus reveal the presence of a subsurface south-polar ocean of water, while an infrared device has detected high temperatures in and around the fractures. Make a list of the requirements for terrestrial-type life—liquid water, organics, minerals, energy and chemical gradients—and you find that Enceladus has it all. Conveniently, the evidence is not hidden beneath the surface—it's coming out into space in the plume. Enceladus is quite willing to "spill the beans".

So now that I've introduced the four suspects, how do we actually tease out their secrets regarding life? It's different for each, but the common thread is direct sampling... flying through a plume, rolling around from site to site or floating across a sea, drilling or melting into an icy surface. And there's more complexity to the answer than just "yes" or "no"—we want to know whether any life we may discover had an independent origin from us.

Such evidence need not be—indeed likely will not be—an entire living organism. More likely is that we will detect and measure signatures that set the chemistry in living organisms apart from abiotic chemistry. Key to this is that, in contrast to non-biological processes, life does not make use of the full range of possible organic molecules. "Biology is built from a selected set".[3] And so if we can recognize patterns in the makeup of organic molecules collected from our suspects— for example, a common building-block molecule with a particular number of carbon atoms, a preferred handedness, or isotopic trends—we then have strong evidence of biology at work. These types of tests are practical for measurements made on a spacecraft in an alien environment millions of miles from Earth.[4]

For Mars however, there is almost as much value in finding the remnants of extinct organisms as there is in finding life itself. And so a search for fossils—presumably microfossils—is well worthwhile. As for extant life on Mars, finding sources of methane and measuring the isotopic composition is one practical way to get at possible life deep beneath the surface. Another is to seek well-preserved organic molecules just below the surface, to see if they record the signatures of biology. Curiosity has tentatively detected organics, but the Mars 2020 rover will do the heavy lifting here.

---

[3] Davila, A. and C. McKay Chance and necessity in biochemistry. *Astrobiology* 14, 2014, p. 534.
[4] An Astrobiology Strategy for the Exploration of Mars. National Research Council, National Academy Press, Washington DC, 2007. Boxes 3.1-3.5.

Life might be abundant in the Europan ocean, or it might be absent: Either way, we do not know how to access oceanic samples to make the determination. The Europa mission now in development will provide the essential information needed to decide, among other things, whether ocean water is welling up through the cracks, and how to access it. We must do this mission before making more ambitious plans to search for life on Europa.

For Titan, the search for life should target one of the great methane seas, by dropping a capsule capable of floating across its surface. Here the complication is that we don't know what kind of biochemistry we are looking for, and so a generalized search for patterns in molecular structures and abundances that indicate deviation from the randomness of abiotic chemistry is appropriate.

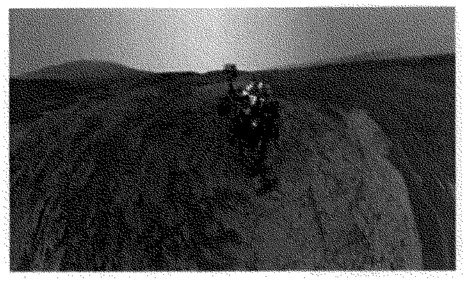
Enceladus provides us potentially with the most straightforward way to look for life signs, given the evidence that the larger ice grains in the plume are frozen seawater from the deep interior. Merely flying through the plume as Cassini has done multiple times, with modern instrumentation intended to detect life, is sufficient to do the search. It is fair to assume that the basic biochemical building blocks are like those on Earth, since every indication we have from Cassini is that the subsurface ocean would support terrestrial microbes. One might even contemplate returning samples to Earth, though an in-situ exploration seems the right first step given the ease with which it can be done.

At the beginning of this testimony I gave you a historical perspective of the kind of progress that has been made over the past 20 years. The current pace of missions and flight times makes it highly unlikely life will be detected in the outer solar system in the next decade, but there is an outside chance that Mars 2020 could find such evidence on Mars in that time frame. For the outer solar system I am more sanguine about a 20-year horizon—new missions to Enceladus and Titan could arrive by the early 2030's, and a follow-on to the currently planned Europa mission might be mounted in time to arrive late in that decade. The long flight times in the outer solar system—5 years to Jupiter, 8+ to Saturn—dictate that planning for these missions must begin now if they are to happen in 20 years.

None of this will happen without the will of the nation to conduct an aggressive program of planetary exploration. The US has been the clear leader in this endeavor, but the absence of proactive planning and funding in recent years has built into outer solar system exploration a gap of a decade between the end of Juno and Cassini and the arrival of the Europa mission. Looking at how much we have done and discovered in the past twenty years, I hope that we as a nation decide to pursue with renewed vigor this remarkable and noble endeavor. Should we do so, there will be even more remarkable discoveries to come.

Thank you for this opportunity to speak today.

Figures



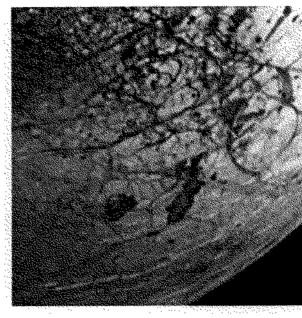


Figure 1 (credit NASA/JPL-Caltech/MSSS)

Figure 2 (credit NASA/JPL)

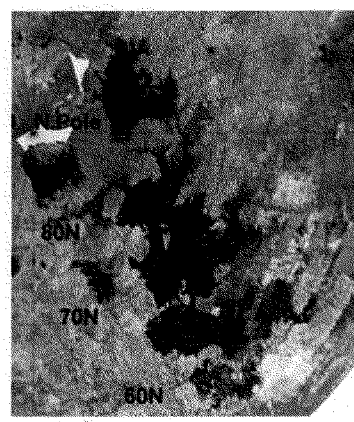


Figure 3 (credit NASA/JPL-Caltech/USGS)

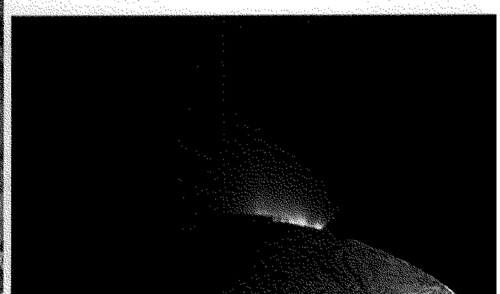


Figure 4 (credit NASA/JPL-Caltech/ Space Science Institute)

Jonathan I. Lunine is the David C. Duncan Professor in the Physical Sciences and the Director of the Cornell Center for Astrophysics and Planetary Science at Cornell University. He is a planetary scientist specializing in astrobiology, the outer Solar System, the formation of planetary systems, and properties of extrasolar planets. His work has led to significant advances in understanding the formation and evolution of planets and moons in our neighborhood and around other stars, with particular emphasis on Saturn's satellite Titan. He has co-authored or authored 294 peer-reviewed publications.

He has made outstanding contributions to the ongoing Cassini–Huygens mission as a Cassini interdisciplinary scientist, Huygens team co-investigator, and Cassini Radar Team member. In addition, he is a co-investigator on the Juno mission, on the near-IR spectrometer ("MISE") selected for the NASA Europa mission, and is interdisciplinary scientist for astrobiology on the James Webb Space Telescope. Lunine is also at the heart of the dissemination of planetary sciences and the education of the next generation of scientists, having written two textbooks and delivered a considerable number of lectures and public conferences. He has participated in or chaired numerous committees for NASA, NSF, and the National Research Council (most recently serving as co-chair of the NRC Committee on Human Spaceflight). He is a member of the US National Academy of Sciences and the International Academy of Astronautics. He is a fellow of the American Association for the Advancement of Science, and of the American Geophysical Union. He served as chair of the Division for Planetary Sciences of the American Astronomical Society, the professional organization of planetary scientists, from 2008-9.

For his accomplishments in the field of planetary sciences he has received a number of recognitions and awards, among which are the Harold C. Urey Prize of the Division for Planetary Sciences of the American Astronomical Society (1988), the Zeldovich Award of Commission B of COSPAR (1990), the James B. Macelwane Medal of the American Geophysical Union (1995), the Basic Science Award of the International Academy of Astronautics (2009), and the Jean Dominique Cassini Medal of the European Geosciences Union (2015). He received a B.S. (magna cum laude) from the University of Rochester in 1980, and a Ph.D. in Planetary Science from the California Institute of Technology in 1985.

Chairman SMITH. Thank you, Dr. Lunine.
And Dr. Bean.

TESTIMONY OF DR. JACOB BEAN, ASSISTANT PROFESSOR, DEPARTMENTS OF ASTRONOMY AND ASTROPHYSICS, GEOPHYSICS, UNIVERSITY OF CHICAGO

Dr. BEAN. Mr. Chairman and Members of the Committee, good morning, and thank you for the opportunity to serve as a witness for this important hearing.

My testimony today will be focused on the topic of exoplanet spectroscopy in the context of the search for life beyond Earth. The main point I want to convey is that an expanded exoplanet exploration program with a flagship exoplanet spectroscopy space telescope as its centerpiece could answer one of humanity's most fundamental questions: Is there life elsewhere in the universe?

Extrasolar planets, or exoplanets for short, are planets outside our solar system that orbit stars other than our Sun. This year marks just the 20th anniversary of the first detection of an exoplanet orbiting a sun-like star, but progress in the field has been rapid in the intervening years. In particular, the launch of NASA's Kepler telescope in 2009 has revolutionized the field. The Kepler mission has advanced to the point that it is now focused on finding Earth-size planets orbiting their host stars in the so-called "habitable zone," which is the distance at which the temperature on the surface of a terrestrial planet could be right for liquid water to be present.

A handful of Earth-size habitable-zone exoplanets have been found over the last few years. These discoveries have grabbed the attention of the scientific community and the public because they suggest that Earth-like planets may exist around relatively nearby stars, and that we therefore have it within our grasp to search for life on other worlds in our lifetimes.

The next step towards determining if there are any truly habitable planets or even inhabited planets is to study the atmospheres of candidate worlds using the technique of astronomical spectroscopy. Planetary atmospheres are a key factor controlling the habitability of a planet because they are reservoirs of biogenic elements and regulators of planetary surface conditions. Furthermore, planetary atmospheres can be influenced by interactions with a biosphere, and thus may be a marker of life itself absent direct observation or communication.

Astronomers have made progress revealing the nature of the atmospheres of hot, gas giant-type exoplanets using the Hubble and Spitzer Space Telescopes and the ground-based Keck and Gemini telescopes. These investigations have yielded constraints on the abundances of key chemical species, the identification of clouds, and the determinations of temperature maps.

Astronomers eagerly await the launch of the James Webb Space Telescope in 2018. Among its many new important capabilities, the Webb telescope will dramatically extend the reach of exoplanet spectroscopy. It may even have the capability to determine the presence of major molecules like water and carbon dioxide and measure the temperatures of Earth-size exoplanets atmospheres. However, Webb will be hard-pressed to detect evidence for life, only made possible with fortuitous planets, extraordinary performance of the instrument, and large amounts of biosignature gases in the planets themselves.

A flagship space telescope with next-generation optics will likely be needed to detect evidence for life on other Earth-like exoplanets. The astrophysics community is currently ramping up for a Decadal Survey that will prioritize large space missions to follow the Webb telescope.

At the wise urging of NASA leadership, the community is currently developing concepts for telescopes that could take spectra of Earth-like exoplanets in preparation for the decadal selection process. The top-priority space telescope from the previous Decadal Survey, currently dubbed WFIRST–AFTA will have capabilities that lay a foundation for a future life-finder telescope. One of the science goals of the WFIRST–AFTA mission is to obtain improved statistics on the frequency of potentially habitable planets. In addition, NASA is currently considering including an exoplanet spectrometer on the telescope. This instrument would not have the capability to make measurements for Earth-like planets but it would advance the science and technology in that direction.

As a final point, it is important to keep in mind that a future life-finder mission cannot be a success in the absence of other projects. The need for comprehensive knowledge to confront the question of life on other planets is why I think that ultimately an expanded program in exoplanet exploration would be the best way forward. Although a flagship space telescope would be the crown jewel, this program should be driven by the question of life rather than the construction of a single facility. It would take courage and perseverance by scientists, government leaders, and the public all working together to act on this vision and see it through, but our ability to rise to this kind of challenge is what makes America exceptional.

From the Apollo program through the Voyager, Hubble, and Mars Rover programs, with the recent stunning success of the New Horizons mission to Pluto, and today with the launch of the Webb telescope just a few years away, our country leads the way in projects that are lasting milestones of space exploration. The search for life beyond our planet represents the next great space exploration challenge that would continue this legacy.

Mr. Chairman and members of the committee, thank you again for the opportunity to be here as a witness, and I'd be happy to take questions.

[The prepared statement of Dr. Bean follows:]

Statement of Dr. Jacob L. Bean
Assistant Professor of Astronomy & Astrophysics
University of Chicago

before the

Committee on Science, Space, and Technology
U.S. House of Representatives
September 29, 2015

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

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

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

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

Why exoplanet characterization through atmospheric spectroscopy is important

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

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

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

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

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

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

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

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

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

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

A vision for the future: towards a Terrestrial Planet Finder

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

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

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

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

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

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

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

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

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

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

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

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

Biography of Jacob Bean

Jacob Bean is an Assistant Professor of Astronomy & Astrophysics at the University of Chicago. He teaches classes in astronomy and the physical sciences and leads a nine-person research team.

Professor Bean's research is focused on the observational study of planets outside the Solar System ("exoplanets"). Exoplanet characterization using atmospheric spectroscopy has been a major theme of his research over the last five years. He has led research programs on this topic using many of the largest ground-based telescopes and on the *Hubble* and *Spitzer Space Telescopes.* These programs have led to a number of breakthroughs in the field, including the measurement of the first spectrum of a super-Earth planet, the development of a technique for ground-based exoplanet spectroscopy observations, the first detection of clouds in a super-Earth atmosphere, a precise measurement of the water abundance in an exoplanet atmosphere, and the determination of the most detailed temperature map of an exoplanet. These results were published in papers in high-impact journals (including Nature and Science) and were widely reported by the popular media (including NPR and The New York Times).

In addition to carrying out research programs with existing facilities, Prof. Bean is also involved in developing new instrumentation for exoplanet detection and characterization. His research group develops new instruments for ground-based telescopes, and he serves on committees that advise national and international organizations on new instrument development (e.g., NASA and the Gemini Observatory). Prof. Bean is currently participating in the design of the Giant Magellan Telescope, which will be the world's largest telescope when it is completed early in the next decade.

Prof. Bean is originally from Chatsworth, Georgia. He received an undergraduate degree in Physics from the Georgia Institute of Technology in 2002, and he received a PhD in Astronomy from the University of Texas at Austin in 2007. He has held postdoctoral appointments in Germany and at Harvard University. His honors and awards include Marie Curie, Sagan, Sloan, and Packard Fellowships. He has been at the University of Chicago since 2011

Prof. Bean lives in Chicago with his wife Ashley and their two young children Kathryn and David.

Chairman SMITH. Thank you, Dr. Bean.
And Dr. Siemion.

TESTIMONY OF DR. ANDREW SIEMION, DIRECTOR, SETI RESEARCH CENTER, UNIVERSITY OF CALIFORNIA, BERKELEY

Dr. SIEMION. Chairman Smith, Ranking Member Johnson, and Members of the Committee, thank you for the opportunity to testify today.

Searches for Extraterrestrial Intelligence, SETI experiments, seek to determine the distribution of advanced life in the universe through detecting the presence of technology, usually by searching for electromagnetic radiation from communication technology, but also by searching for evidence of large-scale energy usage or interstellar propulsion. Technology is thus used as a proxy for intelligence. If an advanced technology exists, so, too, does the advanced life that created it.

We know of no way to directly detect intelligent life, but if other intelligent life exists and possesses a technological capability similar to our own, we could detect their technology using the techniques of modern astronomy. Large radio telescopes such as the Green Bank Telescope in West Virginia and the Arecibo Observatory in Puerto Rico are superb facilities for a wide range of astronomy, including pulsar studies that test Einstein's theory of general relativity, mapping the gas in nearby galaxies, and probing the earliest epochs of the universe. In addition, these facilities are among the world's best in searching for the faint whispers of distant technologies.

A variety of radio study experiments are underway at both the Green Bank Telescope and the Arecibo Observatory, including some that allow us to observe in parallel with other astronomers without interfering with their work, a technique we call "piggyback observing." Several other U.S. and international radio telescopes are also currently being used for radio study, including the private Allen Telescope Array in northern California, the Low-Frequency Array in Europe, and the Murchison Widefield Array in Australia.

Many radio study searches are taking advantage of the wealth of new information on our galaxy's exoplanet population now being revealed by missions such as NASA's Kepler spacecraft.

In a very exciting new project, a group based at the University of California San Diego are using the Lick Observatory near San Jose to conduct a search for pulsed lasers in the near-infrared, wavelengths just a hair longer than optical light but much better at penetrating the dusty space between the stars.

These SETI experiments are funded by a combination of government and private sources, including notable contributions from the John Templeton Foundation. Ensuring that facilities like the Green Bank Telescope, Arecibo, and the Lick and Keck Observatories continue to exist as world-class astronomical facilities is critical to their continued use in SETI experiments.

One of the most exciting prospects for SETI in the next decade is the Breakthrough Listen initiative, a $100 million, ten-year effort funded by the Breakthrough Prize Foundation that will conduct the most sensitive, comprehensive, and intensive search for advanced intelligent life on other worlds ever performed.

I have an animation I would like to show you illustrating some components of Breakthrough Listen.

[Slide.]

Here, we see the Milky Way Galaxy, a galaxy that we now know hosts tens of billions of planets in the habitable zone of their star, planets that might have liquid water on their surface. If intelligent life arose on some of these planets and developed radio technology, the emissions from their technology would proceed at the speed of light out into the Milky Way. But for how long? Life may arise, it may develop intelligence, and finally, a communicative technology. But that final stage may only last for a few thousand years. But the evidence of their technology, the bubble of their electromagnetic radiation, will continue to propagate throughout the galaxy and could eventually be detectable at the Earth.

With Breakthrough Listen, we will conduct deep observations for these types of emissions from 1 million of the nearest stars to the Earth that will be at least 10 times more sensitive than ever performed. These observations will cover at least five times more of the radio spectrum than any previous experiment. We will conduct these observations using the Green Bank Telescope in West Virginia, as well as the Parkes Radio Telescope in Australia.

It is undoubtable that the next decade will be an incredibly exciting time for astrobiology. Data provided by missions like the Transiting Exoplanet Survey Satellite and the James Webb Space Telescope virtually guarantee dramatic new insight into exoplanet science, including identifying and characterizing some of the nearest exoplanets to the Earth. At the same time, we will continue to learn more about the development of life on Earth and the potential for life elsewhere in our own solar system. If history is any guide, these discoveries will only heighten our imagination about the possibilities for advanced life elsewhere in the universe.

Thank you.

[The prepared statement of Dr. Siemion follows:]

Astrobiology and the Search for Life Beyond Earth in the Next Decade

Statement of

Dr. Andrew Siemion
Berkeley SETI Research Center, University of California, Berkeley
ASTRON – Netherlands Institute for Radio Astronomy, Dwingeloo, Netherlands
Radboud University, Nijmegen, Netherlands

to the

Committee on Science, Space and Technology
United States House of Representatives
114th United States Congress

September 29, 2015

Chairman Smith, Ranking Member Johnson and Members of the Committee, thank you for the opportunity to testify today.

Overview

Nearly 14 billion years ago, our universe was born from a swirling quantum soup, in a spectacular and dynamic event known as the "big bang." After several hundred million years, the first stars lit up the cosmos, and many hundreds of millions of years later, the remnants of countless stellar explosions coalesced into the first planetary systems. Somehow, through a process still not understood, the laws of physics guiding the unfolding of our universe gave rise to self-replicating organisms – life. Yet more perplexing, this life eventually evolved a capacity to know its universe, to study it, and to question its own existence. Did this happen many times? If it did, how? If it didn't, why?

SETI (Search for ExtraTerrestrial Intelligence) experiments seek to determine the distribution of advanced life in the universe through detecting the presence of technology, usually by searching for electromagnetic emission from communication technology, but also by searching for evidence of large scale energy usage or interstellar propulsion. Technology is thus used as a proxy for intelligence – if an advanced technology exists, so to does the advanced life that created it. Although natural astrophysical sources produce a diverse array of electromagnetic, gravitational and high energy particle emission, there are particular types of emission that, as far as we know, could only be generated by an advanced technology. For example, technology constructed by human beings has been producing radio emission for more than 100 years that would be readily detectable at dozens of light years using receiving technology only moderately more advanced than our own. Some emission, including that produced by the planetary radars at Arecibo Observatory and the NASA Deep Space Network, would be detectable across our galaxy.

Technologies far more advanced than our own could potentially produce even more dramatic evidence of their presence. Large stellar-scale structures could cause apparent modulation in starlight as they orbited their host, and massive energy usage by a super advanced civilization might be revealed by its thermodynamic signature, even from millions of light-years away.

Although we know of only one example of life anywhere in the universe, we have reasons to be optimistic about the possibility of life beyond Earth. Earth-like planets, water and complex chemistry have now been found in abundance throughout our galaxy. Everything that we believe was necessary for life to begin on Earth is now known to be ubiquitous throughout our galaxy and beyond. Knowing that extraterrestrial life could exist, the race is on to discover whether or not it, in fact, does exist. Yet more compelling is the possibility that extraterrestrial life may have followed a similar developmental process as life on the Earth, and given rise to a life form possessing intelligence and a technological capability similar to, or perhaps far exceeding, our own. Conducting direct searches for advanced extraterrestrial life is the sole means of determining the prevalence of such life in the universe, and answering one of our most fundamental questions: Are we alone?

Radio and Optical SETI

The motivation for radio searches for extraterrestrial intelligence can be summarized as follows: 1. coherent radio emission is commonly produced by advanced technology (judging by Earth's technological development), 2. electromagnetic radiation can convey information at the maximum velocity currently known to be possible, 3. radio photons are energetically cheap to produce, 4. certain types of coherent radio emissions are easily distinguished from astrophysical background sources, 5. these emissions can transit vast regions of interstellar space relatively unaffected by gas, plasma and dust. These arguments are unaffected by varying assumptions about the motivation of the transmitting intelligence, e.g. whether the signal transmitted is intentional or unintentional, and can be applied roughly equally to a variety of potential signal types or modulation schemes. Modern radio SETI experiments have been ongoing for the last 55 years, but for the most part they have searched only a small fraction of the radio spectrum accessible from the surface of the Earth and have probed only a few nearby stars at high sensitivity.

Large national radio telescopes in the United States, such as the Green Bank Telescope in West Virginia and the Arecibo Observatory in Puerto Rico are superb facilities for a wide range of astronomy, including pulsar studies that could lead to the detection of low-frequency gravitational radiation, mapping the atomic and molecular content of nearby galaxies, and probing the earliest epochs of the universe. In addition, these facilities are among the world's best at searching for the faint whispers of distant technologies. Figure 1 illustrates the natural low noise portion of the radio spectrum between 1–10 GHz, and the approximate locations in the radio spectrum where several different types of terrestrial transmitters produce emission. The Green Bank Telescope and Arecibo Observatory can conduct observations across this entire range of the radio spectrum.

Earlier this year, a group of astronomy, engineering and physics students and staff from our team at UC Berkeley, working with our colleagues from the National Radio Astronomy Observatory, installed a new instrument at the Green Bank Telescope that enables us to conduct SETI observations in parallel with other astronomers, a technique we call "piggy-back" observing. This project was funded by a combination of support from the NASA Astrobiology Program, the National Science Foundation and the John Templeton Foundation, but *NASA no longer provides funding for SETI experiments.*

In addition to the Green Bank Telescope, other radio SETI programs are underway in the United States at Arecibo Observatory and the private Allen Telescope Array in Northern

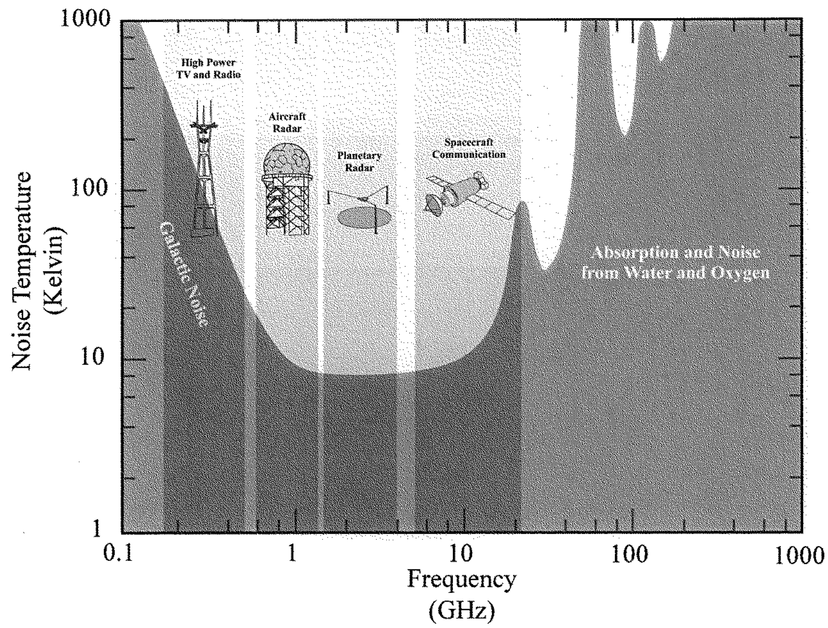


Figure 1: The centimeter-wavelength portion of the electromagnetic spectrum, showing the natural relatively low-noise region between 1-10 GHz. At low frequencies, background radiation from our own galaxy produces significant noise. Above 15 GHz, the oxygen and water in the Earth's atmosphere both attenuates incoming radiation and produces noise. Also indicated in the figure are the approximate locations in the radio spectrum where terrestrial transmitters produce emission.

California. Many international radio telescopes are also currently being used for radio SETI searches, including the Low Frequency Array (LOFAR) in Europe, the Murchison Widefield Array (MWA) in Australia and the Lovell Telescope at Jodrell Bank Observatory in the United Kingdom.

While the dominant paradigm in SETI research involves searching the radio portion of the electromagnetic spectrum, other wavelengths possess merit as well. Similar to our consideration of radio emission from human technology as an example of a potentially detectable signal from extraterrestrial intelligences, we can conceive of ways in which human technologies operating at other wavelengths could produce signatures detectable at interstellar distances. For example, laser technology already developed on Earth could be used to produce a signal that could outshine the sun by many orders of magnitude at a distance of more than 1000 lightyears.

These optical and infrared SETI experiments come in two varieties, searches for pulses of light of short duration and searches for light emission at a single wavelength using a spectrometer. Relative to radio transmissions, optical signals could potentially convey much more information content and are more easily focused for directed signaling or communication.

At one of the world's premier optical telescopes, the Keck Observatory on Mauna Kea, Hawaii (Figure 2), students and faculty at UC Berkeley are pursuing a search for continuous artificial lasers, using optical spectra that are collected for the primary purpose of searching for and characterizing extrasolar planets. In an additional effort, a group led by students and faculty at UC San Diego are using the Lick Observatory, near San Jose, California, to conduct a search for pulsed lasers in the near-infrared part of the electromagnetic spectrum (Figure 3), wavelengths just a hair longer than optical light – the first SETI experiment ever to operate at this wavelength. Other optical SETI experiments are currently operating or under development at Harvard University and several research institutes in France and Italy.

Ensuring that facilities like the Green Bank Telescope, Arecibo and Keck Observatory continue to exist as world class astronomical observatories is critical to their continued availability for SETI experiments.

Figure 2: Optical SETI, searches for laser emission from advanced civilizations, are conducted at the Keck Observatory on Mauna Kea, Hawaii.

Data Mining SETI

The era of the "virtual observatory" has arrived. Many astronomers no longer need to travel thousands of miles to a telescope and command an instrument to perform observations.

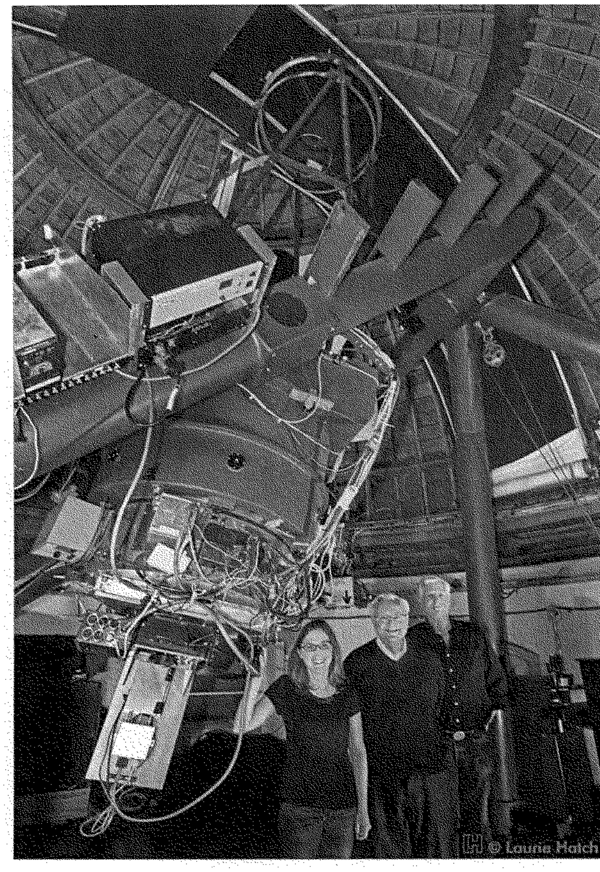
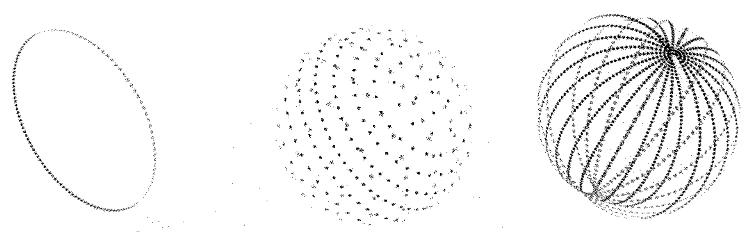


Figure 3: Near-Infrared "Optical" SETI at Lick Observatory. Professor Shelley Wright from UC San Diego (left) leads a team that includes Professor Frank Drake (middle) and Remington Stone (right) using the "Nickel" telescope to search for short pulses of near-infrared light that might originate from an advanced technology.

Hundreds of terabytes of astronomical data, collected with billion dollar telescopes, are now freely available. In many cases, these data are made available to the entire astronomical community the instant they are collected. These data undoubtedly contain many astronomical discoveries that are as yet uncovered. Perhaps, if looked at very closely in a novel way, some of these data contain evidence of an extraterrestrial intelligence.

The astronomical literature is rife with speculation that very advanced intelligences may produce signatures detectable by traditional astronomical observations. Massive "Dyson" structures, so named after they were first proposed by physicist Freeman Dyson, might be be built to harvest the energy of hundreds of Suns and could be detected in the latest generation of infrared sky surveys. Figure 4 shows three hypothetical configurations of these Dyson structures orbiting a parent star. A very advanced civilization using a naturally bright astronomical source as a pseudo-artificial beacon, such as modulation of a naturally expanding and contracting star or interference with a pulsar, could be discovered through careful analysis of variable star or pulsar observations.



(a) (b) (c)

Figure 4: Three hypothetical Dyson structures, a ring (left), and more numerous configurations (middle and right). Such a collection of solar collectors could allow a very advanced civilization to harvest a large fraction of the energy from their star.

Researchers at Penn State University, led by Prof. Jason Wright, have recently undertaken a significant effort to search for evidence of massive energy usage by very advanced civilizations using data from NASA's *WISE* space telescope. Although so far this work has produced only negative results, it has placed significant constraints on the presence of extremely advanced galactic-scale civilizations. Additional work led by Dr. Erik Zackrisson in Sweden and Prof. Michael Garrett in the Netherlands has come to similar conclusions regarding the rarity of super-advanced civilizations, but this collected work represents a promising and growing new area of SETI research.

"Open science" and "open data" policies are incredibly important for enabling innovative SETI research using archive data from national facilities.

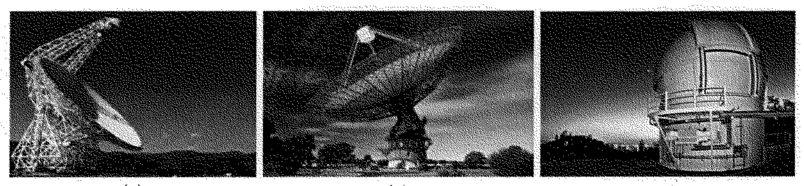
The Next Ten Years

It is undoubtable that the next decade will be an incredibly exciting time for astrobiology. Data provided by missions like the Transiting Exoplanet Survey Satellite (TESS) and the James Webb Space Telescope (JWST) virtually guarantee dramatic new insights into exoplanet science, including identifying and characterizing some of the nearest exoplanets to the Earth. At the same time, we will continue to learn more about the development of life on Earth and the potential for life elsewhere in our own Solar System. If history is any guide, these discoveries will only heighten our imagination about the possibilities for advanced life elsewhere in the Universe. Two of the most exciting prospects for advances in SETI research are described below.

The Breakthrough Prize Foundation[1] has recently announced the Breakthrough *Listen* and *Message* Initiatives[2] – two programs that will investigate the possibility of life beyond Earth and the relationship between humanity and life in the universe. *Breakthrough Listen* is a $100M 10–year effort to conduct the most sensitive, comprehensive and intensive search for advanced intelligent life on other worlds ever performed. Figure 5 shows the three facilities that will be employed in the *Breakthrough Listen* Initiative, the Green Bank Telescope (GBT) in West Virginia (Figure 5a), the Parkes Telescope in New South Wales, Australia (Figure 5b) and the Automated Planet Finder (APF) at Lick Observatory, Mount Hamilton, California (Figure 5c).

Using the GBT and Parkes, *Breakthrough Listen* will conduct deep observations of 1,000,000 of the nearest stars to the Earth that will be at least 10 times more sensitive than ever performed and will cover at least 5 times more of the radio spectrum. *Breakthrough Listen* will also conduct an unprecedented complete survey of the entire plane of the Milky Way Galaxy, as well as surveys of more than 100 other galaxies, including all galaxies in the Milky Way's Local Group. The sensitivity of the Green Bank, expressed as the luminosity (power) detectable as a function of the transmitter distance, is shown in Figure 6. As shown, the Green Bank Telescope could detect an extraterrestrial radio transmitter with the same luminosity as our own most powerful radar (the Arecibo Planetary Radar), in 1 minute each, for more than 1 million nearby stars.

Using a robotic optical telescope at Lick Observatory, the APF with its "Levy Spectrometer," *Breakthrough Listen* will observe 1000 nearby stars and 100 galaxies searching for artificial laser emission. These observations will be performed over wavelengths from 374–950 nm, including the near ultraviolet, the entire visible, and near infrared portion of the electromagnetic spectrum. *Breakthrough Listen* will detect lasers with any power above 100 Watts from the nearest stars and above 1000 Gigawatts from the nearest galaxies.



(a) (b) (c)

Figure 5: The three facilities to be used in the *Breakthrough Listen* Initiative. From left to right, (a) The Green Bank Telescope, Green Bank, West Virginia (b) The Parkes Telescope, New South Wales, Australia (c) The Automated Planet Finder, Lick Observatory, Mount Hamilton, California

The *Square Kilometre Array* (SKA) project is an international partnership that seeks to construct the world's largest radio telescope operating at meter and centimeter wavelengths,

[1] http://breakthroughprize.org
[2] http://breakthroughinitiatives.org

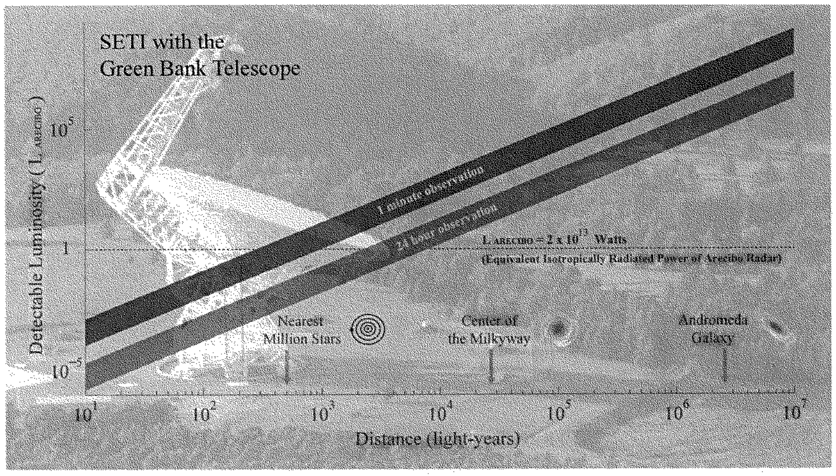
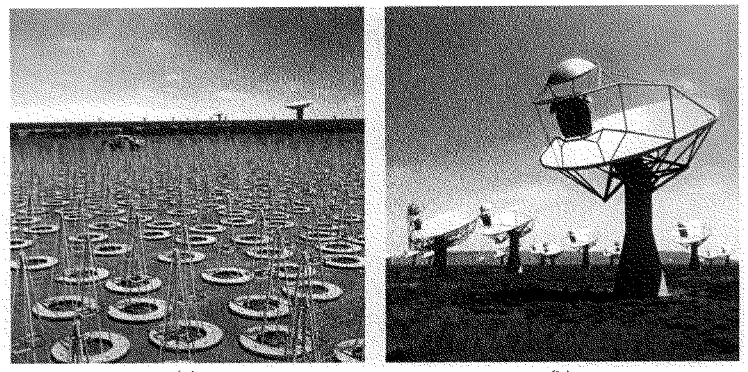


Figure 6: The sensitivity of the Green Bank Telescope expressed as the luminosity detectable as a function of the transmitter distance. Both 1 minute and 24 hour observation durations are indicated. The detectable luminosity is indicated in units of the luminosity of the Arecibo Planetary Radar – the most powerful radio transmitter on Earth. As shown, the Green Bank Telescope could detect a radio transmitter with the same luminosity as the Arecibo Planetary Radar, in 1 minute each, for more than 1 million nearby stars.

eventually achieving a full square kilometer (1 km^2) of collecting area for some components. Such a telescope, as envisioned, would be the most powerful radio telescope in the world, surpassing all current facilities by an order of magnitude or more in sheer sensitivity. Phase I of the SKA is expected to be built in Southern Africa and Southern Australia, with the mid-frequency (centimeter-wave, SKA1-MID) and low frequency (SKA1-LOW, meter-wave) components split between the two sites respectively. The SKA Headquarters is located at the Jodrell Bank Observatory near Manchester, UK. There are 10 SKA member countries, and approximately 100 organizations from 20 countries participating in its development. The United States is not currently an SKA member country.

The SKA will offer revolutionary new observational capabilities for SETI, allowing sensitive targeted SETI observations to be performed alongside other astronomical research. Rather than simply "piggy-backing," SETI observers will be able to independently point the telescope at targets of interest using high speed digital beamforming. SKA construction is expected to be completed in two phases. SKA Phase 1 will include a low frequency (SKA1-LOW, 50 350 MHz) array component made up of 130,000 dipole antennas sited in Southern Australia (Figure 7a) and a 200-dish mid-frequency (SKA1-MID, 350 14000 MHz) component sited in Southern Africa (Figure 7b). SKA Phase 2 will complete telescope construction at both sites and could include augmentation with new mid-frequency aperture array technology that could dramatically expand the telescopes primary field of view.

SKA may be the first telescope capable of detecting truly Earth−like leakage radiation from nearby stars, allowing us our best chance at detecting another civilization with an artificial radio signature similar to our own.



(a) (b)

Figure 7: Artist impressions of the two components of the first phase of the Square Kilometre Array (SKA): SKA1-LOW (left) is a low frequency facility operating from 50−350 MHz sited in Southern Australia. SKA1-MID, operating from 350−14000 MHz will be built in South Africa.

Dr. Andrew P. V. Siemion

Short Narrative Biography

Dr. Andrew Siemion is an astrophysicist at the University of California (UC), Berkeley and serves as Director of the UC Berkeley Center for Search for Extraterrestrial Intelligence (SETI) Research. He is jointly affiliated with The Netherlands Institute for Radio Astronomy (ASTRON) and Radboud University, Nijmegen, Netherlands. Dr. Siemion's research interests include studies of time-variable celestial phenomena, astronomical instrumentation and SETI. Dr. Siemion is one of the leaders of the "Breakthrough Listen Initiative" – a 10 year, 100 million dollar effort, sponsored by Yuri Milner's Breakthrough Prize Foundation, that is conducting the most sensitive, comprehensive and intensive search for advanced extraterrestrial life in history.

Dr. Siemion was a recipient of the Josephine De Kármán Fellowship for Undergraduate Studies at UC Berkeley, the UC Berkeley Dorothea Klumpke Roberts Prize for outstanding scholarship as an undergraduate major in astrophysics and the UC Berkeley Mary Elizabeth Uhl PhD Dissertation Prize for his work on searches for exotic radio phenomena. Dr. Siemion is an elected member of the International Union of Radio Science, in which he serves as an Early Career Representative for the Commission on Radio Astronomy, and the International Academy of Astronautics' SETI Permanent Committee, in which he serves as Committee Secretary. Dr. Siemion also serves on the Science@Cal Advisory Board, Co-Chairs the Cradle of Life Science Working Group for the forthcoming Square Kilometer Array telescope and is a member of the Board of Directors of the Foundation for Investing in Research on SETI Science and Technology (FIRSST).

Breakthrough Listen

Chairman SMITH. Thank you, Dr. Siemion.

As you might guess, we all have thousands of questions and we're somewhat limited in our time by five minutes, but, Dr. Stofan, I'd like to address a couple of questions to you.

One, I am absolutely astounded by the announcement by NASA that briny water may be on the surface of Mars. Is that the case? When the Mars Curiosity Rover reported no evidence of water, I thought that was the end of it, but if we have this water on the surface of Mars, why is it we do not have any photographs of that water?

Dr. STOFAN. Indeed, the new results that we just got show that the recurring slope lineae, these features that are on the sides of some craters on slopes, seasonally over time it seems that water melts——

Chairman SMITH. Right.

Dr. STOFAN. —briny water carries those materials down slope, and we've finally been able to put all the evidence together, including chemical observations, to say, okay, that's really what's forming these things, which we're incredibly excited about.

The problem is these features are very transient. There's not a whole lot of water that's carrying those salts and so it's very hard to see with the resolution of spacecraft that we see. But again, we can certainly trace of the chemical signatures.

We also, at the Phoenix landing site, were able to see the evidence of liquid water, including a little droplet on the spacecraft. So, you know, water is there on Mars. It's not in huge abundance right near the surface but we know it's at the poles, we know it's under——

Chairman SMITH. When will we have evidence of liquid water? Anytime soon?

Dr. STOFAN. I'm afraid I can't answer exactly when will have—we feel that the evidence we showed yesterday is certainly good evidence of liquid water, but you have to understand that those water—when it's flowing on the surface, it's very, very hard to detect.

Chairman SMITH. Okay. Thank you.

Next question is where are we in your opinion most likely to detect any kind, any form of life, even if it's bacteria or microbes or whatever? Is it going to be Mars? Is it going to be Europa? Is it going to be an exoplanet? Is it going to be some technological communication? Where do you think the best prospects lie?

Dr. STOFAN. Well, I certainly believe that it's going to be Mars, and I think, as you heard from me and you heard from Dr. Lunine, we're very optimistic about the 2020 Rover and its potential for looking for signs for ancient microbial life. Now, again, that's——

Chairman SMITH. Okay.

Dr. STOFAN. —not the most exciting in a lot of people's terms to find fossilized microbes, but that's—or the signatures——

Chairman SMITH. Yes.

Dr. STOFAN. —that those microbes existed, but I'm really optimistic, but again, I think it's going to take humans on the surface of Mars to really get at the definitive evidence to study that liquid water——

Chairman SMITH. That we're talking about.

Dr. STOFAN. —that we want to see.

Chairman SMITH. Okay. Thank you, Dr. Stofan.

Dr. Lunine, how would you rank the various—you—let me start again. You mentioned four locations: Mars, Europa, Titan, and Saturn—one of Saturn's moons Enceladus. Was that in order of likelihood or do you have a preference or a prediction as to where we might most likely find evidence of some form of life?

Dr. LUNINE. Well, that was actually in order moving outward from the Sun——

Chairman SMITH. Oh, okay.

Dr. LUNINE. —so there was no implied—or, you know, the question is whether in any environment that can support life does life actually begin, does it form? And I don't know the answer to that and no one else does——

Chairman SMITH. Okay.

Dr. LUNINE. —and that's why in my view we need to look at all of these bodies where there is very strong evidence, compelling evidence of what's called a habitable environment, an environment where life could actually be sustained. So——

Chairman SMITH. And when we find out what the thickness of the ice is on Europa, that's the time to send a probe there I gather?

Dr. LUNINE. Yes. There's a lot of ground work that has to be done on Europa. We don't know if there are organic molecules.

Chairman SMITH. Okay.

Dr. LUNINE. The Europa mission will tell us whether there are fresh organics in the cracks.

Chairman SMITH. Okay.

Dr. LUNINE. If there are, that would be the place to go.

Chairman SMITH. Thank you. Dr. Bean, when do you think we will have the capability of detecting biosignatures in the atmospheres of exoplanets?

Dr. BEAN. Yeah, so as I mentioned, I think the James Webb Space Telescope, which is planned to launch in 2018, will be our first chance——

Chairman SMITH. Right.

Dr. BEAN. —to do that. If we get lucky and we find the kind of planets orbiting very nearby stars, then we may be able to search for biosignature gases——

Chairman SMITH. With James Webb?

Dr. BEAN. Yes.

Chairman SMITH. And not before? You think it's going to take——

Dr. BEAN. Definitely not before.

Chairman SMITH. Okay. I'm going to ask you also what do you think the odds are of actually finding a biosignature, say, in the next ten years. Well, let me ask you, likely or unlikely?

Dr. BEAN. I'd say that's unlikely, but we are optimistic that we can take——

Chairman SMITH. You can say——

Dr. BEAN. —important steps towards doing that over the next 10 years.

Chairman SMITH. Okay. Thank you. Dr. Bean, I was hoping you'd be a little bit more optimistic than that, but anyone want to give a one out of three, one out of four? What would you say?

Dr. BEAN. One out of five.

Chairman SMITH. One out of five, that's better than otherwise. Okay. Thank you, Dr. Bean.

And, Dr. Siemion, last question for you. Could you briefly tell us the advantages and disadvantages of radio and optical astronomy? I know we're trying both. You seemed to focus a little bit more on radio in your comments, but there's advantages and disadvantages to both, and do you have a preference or not, and if so, what are the advantages and disadvantages?

Dr. SIEMION. Yeah, I think you're absolutely right that historically SETI has concentrated on the radio portion of the electromagnetic spectrum.

Chairman SMITH. Yeah.

Dr. SIEMION. But as we've developed technology on Earth that allows us to communicate at optical wavelengths, we've——

Chairman SMITH. Yes.

Dr. SIEMION. —moved some of our efforts in SETI to those wavelengths as well. The truth is is that we don't know what part of the electromagnetic spectrum we might eventually receive, some signal or some evidence of a technological civilization elsewhere. So it behooves us to search as much of that spectrum as we can, and that's why we focus on both the radio and the optical.

Chairman SMITH. Okay. Thank you, Dr. Siemion.

My time is expired but, Dr. Bean, just a quick comment. You know that 20 percent is actually pretty high considering how historic that would be, and I think we all would agree it might be the most interesting news in, say, the last 100 years, so that 20 percent is something I think is not insignificant. So I appreciate your comments.

The Ranking Member, the gentlewoman from Texas, is recognized for her questions. And let me say, going back to her opening statement, that it's not often that the Chairman hears the Ranking Member say she's going to follow the Chairman, so I just wanted to——

Ms. JOHNSON OF TEXAS. If you go to Mars.

Chairman SMITH. All yours.

Ms. JOHNSON OF TEXAS. Thank you very much, Mr. Chairman.

Dr. Lunine, today, we are speaking primarily about astrobiology that can be carried out robotically. However, humans will one day return to deep space and carry out scientific exploration on bodies such as Mars. To that end, it has been over a year since the National Academies released the Pathways to Exploration study, which you co-authored. That report found that the horizon goal for human space exploration is Mars, and as you may know, this Committee agrees with that. Has NASA been in discussions with you on the results of that report? And if so, what is the status of the response of that report and how can this Committee be helpful?

Dr. LUNINE. Well, the NASA Advisory Committee did actually have a session at one of their meetings on the subject of our report, and one of our committee members, Mary Lynne Dittmar, was there and had a dialogue with the committee and also folks from NASA, including Bill Gerstenmaier. So I think there's some dialogue and thinking going on. I look forward to having more dialogue with NASA on the report. I think it's still very fresh and has a lot to contribute to the question of how and when humans will move beyond low-Earth orbit, and so I look forward to that dialogue.

Ms. JOHNSON OF TEXAS. Good. In your view, what if any of the issues does this Committee and the Congress need to address?

Dr. LUNINE. In the context of that report?

Ms. JOHNSON OF TEXAS. Yes.

Dr. LUNINE. Well, you know, to quote from that report, we were concerned about the question of flight rates in the near term and the question of how the destinations or pathways might be chosen, and I still think those are the key operative elements in the recommendations from our report.

Ms. JOHNSON OF TEXAS. Thirty years from now, elementary school children will be leading the scientific exploration of the solar system and beyond. Our knowledge of other bodies near and far will have changed. Humans may have visited Mars and even the two of us here in this Committee won't be around. But life beyond Earth may have been detected by then. So I would like to ask all the panel members, as we think about where we are today and where we might be 30 years from now, is there anything that Congress should be considering to ensure that today's schoolchildren are well-equipped to lead a new era that can include knowledge of life beyond Earth?

Dr. STOFAN. I'm a strong believer that NASA plays an incredibly important role in inspiring the next generation. And Charlie Bolden loves to say that everything we do at NASA is about STEM education. Every time we launch a rocket, every time we do something like encountering Pluto, we are inspiring the next generation to want to explore, to question why. And I would like to see NASA stay on the steady course we have been with obviously this Committee's support to continue that exploration and move forward with moving humans out beyond the low-Earth orbit.

Dr. LUNINE. This nation has done some incredible things in exploring the solar system. One example that excites school kids is the Cassini spacecraft can actually probe the large methane seas of Titan and determine their depths and their composition by sending radio signals through those seas as it flies by Titan. And so we're actually doing ocean exploration a billion miles away from the Earth, and that's only one example. School kids are fascinated by that. They want to be a part of it. And in order for them to be a part of it, we have to have continuity in exploration. We have to continue these wonderful missions so that there isn't effectively a generation-long gap in these discoveries.

Dr. BEAN. To get back at Chairman Smith's earlier question about putting a number on the chance of finding life, I want to emphasize that scientific process is a step-by-step, deliberate process, and so being able to maintain, like Jonathan said, a continuity in funding these programs and continuing this deliberate approach I think is extremely important.

Dr. SIEMION. I think the only thing that I have to add to what my other panel members have said is is that the search for life I think has a particularly compelling aspect to it for young people, and I think to the extent that that can be highlighted and taken advantage of to encourage more young people to enter careers into space and science and technology is wonderful.

Ms. JOHNSON OF TEXAS. Thank you very much. My time is expired.

Chairman SMITH. Thank you, Ms. Johnson.

The gentleman from Texas, Mr. Babin, the Chairman of the Space Subcommittee, is recognized for his questions.

Mr. BABIN. Yes, sir. Thank you, Mr. Chairman. And welcome all of you panelists. We appreciate and it's very, very fascinating to hear your testimony.

In my district, Texas 36, the Johnson Space Center Astromaterials Curation facility provides the services for all return planetary materials that do not require planetary protection laboratories. This facility has been in operation since the Apollo lunar samples were returned. In the next decades we anticipate missions to collect samples from the Moon, from Mars, from comets, and from asteroids. Each of these new sample collections will require new curation laboratories while the facilities for the older collections will require routine maintenance and upgrades.

Samples to be returned from Mars pose even greater challenges due to special planetary protection requirements. Dr. Stofan, what steps is NASA taking to upgrade its curation facilities and protect against the transfer of viable organisms from Earth to celestial bodies, which may harbor life?

Dr. STOFAN. We have two different committees at NASA, certainly, the Planetary Protection Group where we take these issues extremely seriously both for forward contamination of Mars and the backward contamination for when we eventually return samples to the Earth. So that's one aspect of where we are certainly doing research. We're doing testing of all our Mars spacecraft in the planetary protection area.

We also have another group where we reach out into the community and bring experts in to advise us on our curation. I had the opportunity just this past year to tour the facility down at Johnson. It's extremely—it's an amazing facility. It's really fun to be able to go there and look at the Apollo lunar samples, the meteorites we've returned from Antarctica. And we take that facility, its preservation, and its eventual expansion as we move eventually towards bringing samples back from Mars. So we certainly work closely with the community to understand what is needed and to make sure we will eventually, when we do return samples from Mars, we will have a plan in place.

Mr. BABIN. Thank you very much.

And this is directed to everyone. What proportion of astrobiology research in the United States is funded directly or indirectly by NASA? Does anyone know? Okay.

Dr. STOFAN. No. We at NASA can certainly take that question for the record.

Mr. BABIN. Um-hum.

Dr. STOFAN. I will say I was just talking with someone a few weeks ago. I was at a conference at Ames Research Center where we were thinking about climate on extrasolar planets, and it's one of the reasons, as I mentioned in my testimony, that this whole area of astrobiology is an amazing one and it actually makes me think it'll be a little hard to pull the number out. We can certainly get you a number on the exact funding—

Mr. BABIN. Okay.

Dr. STOFAN. —but when you're thinking about, for example, habitable conditions on stars, you have to be doing heliophysics to understand stars, the wind—that solar wind, the interior of the planet, does it have a magnetosphere that then protects that atmosphere from being stripped away? The work we do here on Earth to understand extremophiles, planetary science, we're pulling from so many disciplines, which is to me what makes this area of science in particular so incredibly exciting and fruitful. It's truly interdisciplinary.

Mr. BABIN. Absolutely. Okay. And also what are the most important technological advancements that are needed to further astrobiology research and what advancements should be our highest priority to continue this?

Dr. LUNINE. Well, I'll take one crack at this. And I don't want to prioritize these, but one in my area is to develop miniaturized instrumentation that can detect the chemical signs of life and also detect biological activity. The smaller the instruments, the easier it's going to be to send them to the planets.

Dr. BEAN. From the standpoint of studying exoplanets, I talked in my testimony about building a very large space telescope as a flagship mission. That's a very high-tech thing that we have to do to take direct images of planets that we can take spectra from and look for the signatures of biosignature gases. That involves the construction of large space telescopes, rockets to put those telescopes into orbit, instrumentation to block the blinding glare of the stars those planets orbit, and perhaps even the manned spaceflight program to service those telescopes or even construct the telescopes in orbit.

Mr. BABIN. Thank you.

Dr. SIEMION. I think in the search for extraterrestrial intelligence, the low-hanging fruit is very much digital signal processing technology, so improving our ability to process the very, very high data rate streams that are produced by radio telescopes and some optical telescopes, and also developing receiver technology for radio telescopes that allow us to use old facilities in new ways.

Mr. BABIN. Right, thank you. Mr. Chairman, I yield back the balance of my time. Thank you, panelists.

Chairman SMITH. Thank you, Mr. Babin.

The gentlewoman from Connecticut, Ms. Esty, is recognized for her questions.

Ms. ESTY. Thank you, Mr. Chairman, and thank you, Ranking Member Johnson, for holding today's fascinating hearing. And thank you to all of you.

I joined millions of Americans on Sunday night watching the Blood Moon and a Blue Moon earlier this year, and I have to tell you, in the district like mine in Connecticut, schoolchildren are incredibly inspired and excited by these developments. And many of us here on this panel share a commitment to STEM education. And so it's in part through that lens I would like to proceed with my questions.

Congratulations, Dr. Stofan, incredibly exciting announcement yesterday. And we look forward to understanding what that means. And as you can hear, we've already had questions today.

Dr. Stofan, you spoke earlier about the need to have human exploration on Mars to really understand and to make those subtle intuitive judgments that are necessary. Do you anticipate that yesterday's announcement and the discovery proceeding that changes in any way the priorities of the ordering of that? And help us understand our role as decision-makers on helping to set priorities that are keeping up with the developing science.

Dr. STOFAN. You know, I think one of the most exciting things about yesterday is the fact that we now know there's near-surface liquid water on Mars. And so this idea that Jonathan Lunine mentioned in his testimony of—you know, again, because of this length of water—time that we know that water was stable on Mars, that's what makes scientists think that Mars is the place where life maybe could have evolved because not only did you have liquid water but you had the time to allow the chemical reactions to take place.

The exciting thing about knowing there's near-surface water is saying maybe there could still be life forms on Mars today deep underground, several meters below ground where the cosmic radiation that affects Mars would not affect them, but the idea that it's potentially accessible to be studied by, again, astronauts and laboratories on the surface of Mars. And again, as a field geologist, somebody who likes to go out in the field and crack open rocks, I just have this strong bias that it's going to take humans, laboratories a lot of work because, again, when you're—it's one thing if you're looking for something large. If you're looking for something small, it's going to take time and it's going to take effort, and that's why I think humans are so critical. And that's why NASA has chosen to be on this path. And I think the findings from yesterday convince us we're on the correct path.

Ms. ESTY. Thank you. And I have to confess I have a son who did astrophysics and did exoplanet things, so I have a personal—I know he has a personal interest in discovering if this manned mission is going to keep up with his fourth-grade project from, you know, about 15 years ago.

Dr. Lunine, I was particularly struck by your comment that a key issue is whether in a habitable environment life actually does develop, which is sort of the opposite of where we start. We started with this search is there any life out there, and now it seems to me you're asking a very different question, which is we see a lot of components that we would think ought to lead to life; does it lead to life or does it not? What are the technological breakthroughs you see us needing to support—to answer that somewhat different question? It seems to me that's a different question than I certainly would have thought about five years ago.

Dr. LUNINE. Well, it's a different question but it's a related question. We really have no laboratory model for how life began on the Earth. No one has done this in the laboratory. And so one of the reasons for going out to environments in our solar system where the conditions for life are apparently there and possible is to see whether life actually began, essentially to do the experiment in the field instead of in the laboratory. And the critical things we need for that are devices to analyze abundances of amino acids, fatty acids, to look for patterns in other molecules that might be part of an exotic biochemistry, for example, on Titan.

Part of the problem is that it's not entirely clear what we want to look for in some environments. In other environments like Mars, Europa, Enceladus it's very clear what we want to look for. So chemical analysis is critical and the ability to get out to these planets and sample planets and moons and sample them is also critical.

Ms. ESTY. Thank you. And if we might be able to follow up afterwards with some more detail because, again, our job is in part to try to set funding priorities and they need to take into account these changes, so I think, Dr. Stofan, your comments about the near-surface presence of water compared with, say, Europa where it's so deep and that presents harder technological challenges may help guide us with the—as I'm afraid we have to say the not-enough money that we have to do this research. I wish we had more, but with what we have, we want to make sure it has the most impact and rely on your judgment in guiding us. Thank you all very much.

Chairman SMITH. Um-hum. Thank you, Ms. Esty.

The gentleman from Louisiana, Mr. Abraham, is recognized.

Mr. ABRAHAM. Thank you, Mr. Chairman.

I'm one of those teenagers that rushed home to see the original Star Trek with William Shatner and Leonard Nimoy, so this is fascinating. Like the Chairman said, we have a million questions.

Dr. Stofan, like you, I'm of the opinion you're going to have to have boots on the ground so to speak to finally answer the questions. So let's bring it a little bit closer to home. You referenced the possible meteor asteroid in Antarctica. I'm assuming you're referencing the Allan Hills meteor back in, what, '84 I think it was when it was discovered.

And if we go to a synthetic biology topics such as XNA as opposed to DNA, RNA, would our funding be more appropriate in a realistic term as to funding projects in that realm as opposed to, you know, something that maybe 100 years off as far as time travel or space travel is concerned?

Dr. STOFAN. Well, I certainly think that this is a multi—as I said, it's a so interdisciplinary that you really need a multipronged approach. And so I think that's what NASA has developed by saying we do need boots on the ground. I personally think it's achievable that we meet the President's goal of getting humans in the Mars vicinity in the 2030s. I think it's completely doable. And in the meantime of course continuing our robotic exploration like we're doing with the Mars 2020, moving with the Europa mission to go and explore Europa.

So I don't think it's an either/or; I think it's an "and." We need to do the technology research here on the ground. We need to do biological research, and certainly synthetic biology is an amazing expanding field at this point in time. But I think it's all of those things together that help us move forward scientifically and help us refine scientific questions as we move forward.

Mr. ABRAHAM. And you've got DARPA, you've got USAR MED you've got NASA, you've got all these agencies looking for other life forms, doing research on genetic engineering and those types of deals. Is there any one agency that is spearheading or that these other agencies report to? Is there any hurding of the cat so to speak where this research can come under one big umbrella and people talk to other agencies and actually come up with some formulations?

Dr. STOFAN. Well, I think in the area of astrobiology this is why community roadmaps like the Astrobiology Community Roadmap that is coming out this year—because in my mind, going to the community, whether it's through the Decadal Survey process through the Academies, the astrobiology roadmap is going out to the community, who—in general, the scientists know where all the funding streams are coming from. They're the ones who are truly pulling and doing this multidisciplinary work. So when you get the community together and say here are the priorities, here are the areas that we think have the most potential for advancement in the next five to ten years, it's that voice of the scientific community that I think helps guide——

Mr. ABRAHAM. But is there one voice at this point or is anybody at the top of the heap so to speak?

Dr. STOFAN. In astrobiology I would argue that NASA is really guiding what we're doing and what the next steps are. We certainly work closely with other agencies, though.

Mr. ABRAHAM. Does NASA have any rules or regulations that they foresee that would limit or harness this potential breakthrough? I mean I could see where with what we have available even now with some of the genetic engineering that, you know, some of this stuff could turn out to be kind of bad stuff.

Dr. STOFAN. We certainly don't have any regulatory authority but I'd have to take that question for the record because I don't know the answer to it.

Mr. ABRAHAM. Okay. Thank you.

Dr. Lunine, just a quick comment on what you had spoken with the Congressman earlier about potential life developing in an environment. Just a personal question: What is your theory on panspermia, the bringing of life forms into our Earth atmosphere on an asteroid or meteor?

Dr. LUNINE. I think that panspermia has occurred certainly between the Earth and Mars. We know that materials are exchanged between those two planets. We have the Allan Hills meteorite. And there are some good studies that have been done that show that amino acids will survive the trip to the Earth through the atmosphere on an asteroid and possibly bacteria as well, so there may well have been extensive exchange of life and biological materials between the Earth and Mars, particularly in the early history of the solar system when impacts were more frequent.

Mr. ABRAHAM. Okay. Thank you, Mr. Chairman. I yield back.

Chairman SMITH. Thank you, Mr. Abraham.

The gentleman from Virginia, Mr. Beyer, is recognized.

Mr. BEYER. Thank you, Mr. Chairman. I thank all of you for coming today. It's a fascinating hearing. Mr. Chairman, thank you very much for structuring this. And I look forward to our Science, Space, and Technology CODEL for low-Earth orbit. I'm counting on you to assist me in this.

To go quickly, Dr. Siemion, you know, for years we had the PCs at our home following SETI, doing the analysis of the work, and it was fun. We have no successful conclusion yet. I'm fascinated by the $100 million for the Breakthrough project. But what happens when we discover extraterrestrial intelligence? Do we have a plan about what happens next?

Dr. SIEMION. Well, I'll just mention that—so SETI at home, the program on PCs, is still around and you're all welcome to download it. It runs on cellular telephones now, as well as home PCs.

I think a lot of people have put a lot of thought into what to do when we potentially eventually discover intelligent life or any kind of life beyond the Earth. I think there will be a range of reactions. I think for my part my personal opinion is that probably the most common reaction will sort of be I sort of—I told you so. I think many people probably believe that life is out there and maybe even intelligent life, and certainly the more we learn about the exoplanet population and water on Mars and these kinds of things I think reinforced with people the possibility. But the truth is is that we really don't know for now, and I think to see what the reaction will actually be we'll probably have to wait and see.

Mr. BEYER. It'd be interesting to have protocols in place for when we finally get the breakthrough, what do we say back and the like so—yeah.

And, Dr. Lunine, you talked about Titan and all the methane and ethane and all that, and I sort of basically understand that most elements only come from the explosion of stars, so you'll get the carbon, but are methane and ethane—can they develop other than biologically?

Dr. LUNINE. Yes. Actually, methane is a very simple organic molecule, and so it occurs in many environments, in interstellar clouds, in—they're in comets. It's measured there. And so these are evidently sources of methane that are not from biology. It's simple to make in the laboratory, for example, and carbon is very abundant, as you alluded to, as one of the products of stellar nucleosynthesis.

So we think that Titan is—has an enormous inventory of methane that is not biological, that was produced by abiotic sources. And the ethane that is also part of that system was produced from the methane, and that's something that Cassini has confirmed for us by measuring the places in the atmosphere where the ethane is produced from the methane by ultraviolet chemistry. So Titan is a huge repository of abiotic methane.

Now, from those and other organic molecules, does some form of life occur on the surface or arise in the seas of Titan? That's the part we don't know.

Mr. BEYER. All right. Thank you.

Dr. Stofan, I think this is for you but maybe Dr. Lunine. Dr. Abraham talked about the panspermia, and I know there was a project that evolved out of Harvard or MIT a few years ago trying to replicate the early origin of life on Earth, you know, the primordial soup, organic soup thing. Is there much evidence that—or any evidence that life on Earth may have started someplace else?

Dr. STOFAN. You know, we just don't know the answer to that. You know, we know—what we do know is that life evolved very rapidly here on Earth after conditions stabilized. And again, that's a factor that makes us optimistic that there's life elsewhere in the solar system knowing that life arose relatively rapidly here.

But we honestly don't know if, again, did Mars—you know, bacteria come from Mars, bacteria from Earth go to Mars? We just don't know that, and that's why it's so critical we think to continue this search for life on Mars, the other bodies of our solar system to answer that very question.

Mr. BEYER. Great, thank you.

Dr. Bean, you're—it's fascinating your photos of Enceladus and the fissure, and the—I was trying to—if you could go a little deeper on—are those gases that are being released from—through the fissure that——

Dr. BEAN. So I think that would be more appropriately addressed to Dr. Lunine if you want to—

Mr. BEYER. Okay. Was it—I'm sorry.

Dr. LUNINE. Yeah, that's okay. I think it was my slide. So——

Mr. BEYER. Okay, great.

Dr. LUNINE. —in the case of Enceladus, those fissures at the south pole have jets of gas and ice emanating from them, and those jets merged to make this a very large plume that was discovered by Cassini. We did not know of the existence of this plume until the Cassini mission. And once the plume was discovered, Cassini was directed to actually fly through the plume multiple times and sample the material in the plume with its instruments. One of the important lessons that we get from this is that these flagship missions with large numbers of instruments are able to respond very flexibly to new discoveries. The instruments actually tasted the material in the plume or designed it to sample the atmosphere of Titan, but once the plume was discovered, Cassini could actually use those same instruments to tell us what the plume is made of.

Mr. BEYER. Okay, great. Thank you very much. Chairman, I yield back.

Chairman SMITH. Thank you, Mr. Beyer.

The gentleman from Florida, Mr. Posey, is recognized.

Mr. POSEY. Thank you, Mr. Chairman, and thank the witnesses for their testimony today.

I just wonder if each of you would give me your definition of life.

Dr. STOFAN. I think it's a something the scientific community really struggles with. You know, certainly there are signs that everybody agrees on, you know, something that is self-replicating, something that consumes a something and excretes something else, but the problem is life here on Earth, what we've learned from doing research here on Earth is that life and the boundary of what's not life and what is life is a little blurry, and that's why this is going to be so challenging to go find life on other planets.

Dr. LUNINE. Life is a self-replicating system that undergoes evolution or mutation and which also seeks to minimize its local entropy, maximize its order in the sense that chemically we use a very small fraction of the possible compounds that can be produced from carbon, and the fact that we're alive is because we can take in large amounts of nutrients, process them to make this very small, specific set of molecules that build our structure, control energy in and out, control the information needed to build these other molecules, and then we expel the rest. So for me as—with my physics background, it's a very high order, very low entropy in a chemical system.

Dr. BEAN. I would say that astronomers use a very basic definition of life because the information that we can get when we study the atmospheres of exoplanets will also be very basic. And so we use a very Earth-centric, even human-centric point of view for life, and that's the thing that we're looking for evidence for in the atmospheres of other worlds.

Dr. SIEMION. I guess there's some advantage to going last on a question like that. I don't know that I have a lot to add to what Dr. Stofan, Lunine, and Bean said. I certainly appreciate the thermodynamic definition of life that Dr. Lunine articulated. I guess maybe the only thing that I would add to that is that I think many of us in the astrobiology community assume that life is something that we'll know when we see it, and hopefully that's true, but we're not sure. And it's quite possible that the first life that we encounter beyond the Earth will be very different than any kind of life that we have on Earth.

Mr. POSEY. Thank you. This question is for each of you. If you could pick a mission, this person would say I want a mission that will do this, achieve this, you know, what particular type of mission would you choose?

Dr. STOFAN. You know, I'm going to go with the geologists on the surface of Mars looking—you know, cracking open lots of rocks looking for life. That's my big payoff mission.

Dr. LUNINE. So I would go with the Europa mission, and the reason for that is we have so much tantalizing evidence that Europa is a habitable environment but there are missing pieces, including whether there are organics and where to actually go search for life. And I personally—and I think we have been waiting since 1998 for a mission to follow up on the Galileo orbiter Discovery of the ocean under Europa. And so from my point of view I think it's a critical mission to do and I would make that my number one right now.

Dr. BEAN. So I would like to see a large space telescope that can take spectra of other Earth-like planets orbiting nearby stars, something very similar to the previously proposed and discussed Terrestrial Planet Finder mission, or TPF, which you may have heard about. I think the advantage of studying extrasolar planets is that we have a chance to look for—to do an experiment so to say on how life arises on terrestrial planets in a variety of environments. So that's what I would like to see.

Dr. SIEMION. I'm not sure what list I'm choosing from here, but as a radio astronomer and someone interested in SETI, I think it would—I'd be remiss to not suggest that it would be wonderful to put a radio telescope on the far side of the Moon. That region of the Moon is protected from radio frequency interference from the Earth, something that confuses us in SETI experiments and allows us to observe at very, very low frequencies very effectively.

Mr. POSEY. Y'all make the choices really tough, don't you?

Following up on the last answer, some people think because we've been to the Moon, we shouldn't return to the Moon. There's some—obviously some strategic reasons for going there for future transportation as a steppingstone to Mars, but I'd like to ask each of you your opinion of whether or not we still have a lot to learn from our own Moon?

Dr. STOFAN. I chaired the Inner Planets Panel for the last Planetary Science Decadal Survey, and in—listed in the New Frontiers collapse of missions is a mission to look at the terrain around the south pole of the Moon where we think the lunar mantle has come very close to the surface to help us understand the origin of the Moon and what that tells us about the origin and evolution of our own planet. So scientifically, we certainly have lots of outstanding questions about the Moon that the scientific community has articulated through the Decadal Surveys.

Dr. LUNINE. The Moon contains the geologic record of the first 2 billion years of the history of the Earth, and that record has been more or less lost on the Earth because the Earth has been so active. And so that is for me the critical aspect of the scientific value of the Moon. That's the time when life began on Earth, and to understand what was happening geologically, we can do no better than turn to the Moon.

Dr. BEAN. I'd like to answer the question in terms of human spaceflight. Dr. Stofan and Dr. Lunine, you gave great scientific answers, but for me, if we can combine science with the human element, I think that's a very powerful thing. That will reach out to the public. That will excite our schoolchildren to follow math and science, and so for me that's an exciting "yes" to that question.

Dr. SIEMION. I think I would agree with Dr. Bean. I think a manned mission to the Moon would be a wonderful steppingstone to future missions to perhaps Mars.

Mr. POSEY. I want to thank y'all again for your testimony. It's really been wonderful and I think everyone enjoyed it.

Thank you, Mr. Chairman.

Chairman SMITH. Thank you, Mr. Posey.

The gentleman from California, Mr. Bera, is recognized for his questions.

Mr. BERA. Thank you, Chairman, and Ranking Member. And I really want to thank both the Chairman and Ranking Member for this topic. You know, it comes at a very timely time—and the witnesses.

You know, as a child growing up in Southern California at the heart of the aerospace industry in the '60s and '70s, you know, the space race captivated us, the Apollo missions, Apollo-Soyuz, Skylab, going to the space shuttle. And, you know, as someone who went into the sciences and became a doctor, you know, it really was pivotal in, you know, fostering our curiosity. I mean if we think about who we are as a race, as human beings, we are naturally curious. We are natural explorers and we want to find those answers.

And I think it's incredibly important, the work that NASA is doing, the work that our scientists are doing and fostering the imagination of the next generation. I think we need to do more of that in fact because, you know, in listening to some of the—your testimony, as well as how you answer the questions, we don't know what life is going to look like. We don't know what we are going to discover. We don't know what frequencies we should be listening for. But we do know that something is out there, and if we don't, you know, continue to push our imagination, if we don't continue to—we don't know how we're going to get to Mars, let alone how we're going to send a human being to Mars and bring them back, but we do know if we challenge ourselves, we will discover that. We will—we always have. And I think that is the importance of what we're doing here on the Science and Technology Committee but also in Congress and also working with our colleagues around this world because this is not just a U.S. mission; it is a human mission to find and discover, you know, where we came from, how life evolved, but also how life becomes extinct as well, as we're looking at these planets, the impacts of those discoveries on, you know, what is affecting our own planet right now as we deal with climate change, as we deal with a changing atmosphere. Those discoveries will help us manage our own issues on our planet.

I'll ask a quick question of each of the panelists, and each of you can answer this. In explaining why it is important to search for life beyond our planet, beyond just the philosophical elements, if you were to explain this to an elementary school student or the public in general, how might you put why this is such an important endeavor? And we'll start with Dr. Stofan.

Dr. STOFAN. You know, I certainly always mention this fact, that ever since I think there have been people looking up at the sky, we've wondered are we alone, and so there is that huge philosophical piece. The other piece I like to talk about is, you know, when we find life, does it have RNA? Does it have DNA? Is its cell structure like our cell structure? And then how can we take that information and look back at life here on Earth and try to understand better how life here involved, what the conditions are? And so to me you do get a tremendous learning about life in general by finding life on other planets.

Obviously also I try to point out to audiences if they don't buy the science and the philosophy stuff, I try to point out to them that when we do great human endeavors, whether it's, you know, exploring the Moon, building the next great telescope, we challenge technology. We bring good technology jobs to this country. We move this country forward in our reputation both internationally and at home. And I think there's that inspiration part of just doing really hard things, accomplishing great things, which this country has demonstrated so ably that were so capable of.

And I will say I also like to tell schoolchildren when I go and talk to them, I say oh, my gosh, you guys have so much work to do. We have 5,000 planets we need you to go study. You know, we've got entries and landings for humans on Mars. You guys better grow up and get to work. We need help.

Mr. BERA. Great.

Dr. LUNINE. This might be a philosophical answer so I apologize for violating the ground rule, but, you know, for the last 500 years we've lived in a kind of a Copernican worldview where the Earth was not the center of the universe or even the solar system; it's a planet in the solar system. The Sun is not at the center of the galaxy; it's just a common star in the galaxy. The galaxy is one of hundreds of billions of galaxies in the cosmos, and yet we are singular. I mean life and intelligent life and ourselves at the moment we know of no other form of life, intelligent life, and the Copernican worldview would say they're all over the place. And it's crucial to test that because if that turns out not to be the case, that's going to shatter our worldview.

Dr. BEAN. So my answer would be more along the lines—of course, those are excellent reasons why we want to do that, and finding out the answer would he absolutely fascinating and change our worldview. But I think also the process of doing it tells us a lot about ourselves, tells us about our hopes and dreams and about, you know, how we can work together as a country and as a society and the world. So for me I want to emphasize the process of looking for that answer, whatever the answer may be, if it's a positive or a negative. But the process—through the process we find out a lot about ourselves.

Dr. SIEMION. So I may be a bit biased but I think that life is the most interesting property of the universe, the idea that somehow in this largely mechanical universe that we live in, that we understand to great detail, some sort of an organism came to be that could question its own existence, that could wonder about the universe itself and where it came from. You know, if we don't understand that, then I think we don't understand perhaps one of the most fundamental properties of the universe that we live in, and so we must answer that question.

Mr. BERA. Great. Thank you.

Chairman SMITH. Thank you, Dr. Bera. And just to follow up on that question if other Members will allow me, just real quickly, yes or no, do you think intelligent life does exist elsewhere in the universe? Dr. Stofan?

Dr. STOFAN. Maybe.

Chairman SMITH. Okay. Dr. Lunine?

Dr. LUNINE. Mr. Chairman, am I allowed to answer by saying I honestly don't know?

Chairman SMITH. No, that's a legitimate answer. Members of Congress should give that more often themselves. Dr. Bean?

Dr. BEAN. I don't know either.

Chairman SMITH. And Dr. Siemion? I'm not asking you if you know; I'm just asking you if you think.

Dr. SIEMION. I also don't know but I think it would be incredibly strange if we were the only example of intelligent life in the universe. And——

Chairman SMITH. Okay.

Dr. SIEMION. —I'll quote Stephen Hawking just very, very briefly, someone much smarter than I am. A universe in which intelligent life only exists in one place and a universe in which intelligent life potentially exists in many, many places are very, very different places.

Chairman SMITH. Very good. Thank you, Dr. Siemion.

We'll go now to a gentleman from California, Mr. Swalwell, for his questions.

Mr. SWALWELL. Thank you, Chair. And thank you to our panelists. Congratulations. I have to say it's refreshing to have a hearing about something so big, so exciting and further than the eye can see, and so, you know, in Washington it gets quite frustrating here. It feels like we are so focused on just very small, incremental things and people at home get quite frustrated that that seems to rule the day here. But the work that you're doing is so important, so big, and will inspire so many future scientists. So congratulations.

I had the opportunity to go with the Chairman and a few others to Antarctica. One of your colleagues, John Gunderson, joined us on a trip and he told us as we went through the McMurdo Dry Valleys, that that area—and he was excited to be on that trip and visit that area because it most closely resembled what we believe many of the parts of Mars to be. And so this discovery is another step forward in that effort.

As far as the water that has been discovered, do we believe it could support life? Is it too salty? Do we know enough about its properties to make that conclusion yet? Dr. Stofan?

Dr. STOFAN. It certainly makes us concerned that that water in particular had a lot of perchlorates in it and salts, and so based on—you know, and this is where everything we say—you know, based on what we know about life on Earth, that would not be a very habitable type of water. That being said, what we know about the Earth is like this. What could be is like that. So fundamentally we don't know.

Mr. SWALWELL. Great. Any other thoughts from the panelists on that question?

Dr. LUNINE. Well, just very briefly, if I talk about the possibility of looking for exotic biochemistries on Titan, I'd better not say that life is impossible in the perchlorate solutions on Mars, which would be a lot easier to imagine the biochemistries. So, yes, terrestrial life as we know it, bacteria, et cetera, would all be sterilized by that solution. But is there a form of life that has evolved to live in that solution? That would be very interesting but not impossible.

Mr. SWALWELL. And speaking of sterilizing, according to the New York Times, "NASA has no plans to examine closely any of these places which may contain water or could be potentially habitable places out of fear of contaminating them with Earth's microbes." So sterilizing probes is expensive. Do you think it's time to reexamine this approach so we can follow up on this latest discovery?

Dr. STOFAN. You know, I think the scientific community right now, not just in the United States but around the world is—you know, because obviously planetary protection is something that's governed by international policies and procedures, we want to make sure that if we find life on Mars, we know that we've found life that is Martian life, not contamination we brought from the Earth.

And so certainly in areas where there are water, we need to be cautious, extremely cautious as we move towards exploring them. However, those areas could potentially be the most interesting areas to explore. And so I think the scientific community is certainly going through a process right now of saying, okay, right now, we don't think that's the place to run to and potentially contaminate so let's take a really measured, very scientific approach to how we might get at exploring those regions. Obviously, when we eventually send humans to Mars, that's going to lead to much likely broader-scale contamination, and so I think it's important as we lead up to sending humans to Mars we try to keep Mars as pristine as we can.

Mr. SWALWELL. Great. And finally, 38 million Californians are wondering: Can we get that water to California?

Dr. STOFAN. Certainly the California drought is something that NASA is very concerned about. We've been using our satellites to do what we can to help to certainly monitor with the GRACE data. And we've certainly seen the alarming reduction in the amount of water in the aquifers. And we've been working on some projects with farmers in California that have—and some pilot projects that have reduced water usage by as much as 30 percent. So NASA is trying to help.

Mr. SWALWELL. That's great. Thank you. I yield back. Thank you, Chairman.

Chairman SMITH. Thank you, Mr. Swalwell.

The gentlewoman from Maryland, the Vice—excuse me, the Ranking Member of the Space Subcommittee is recognized for her questions.

Ms. EDWARDS. Thank you very much, Mr. Chairman, and thank you to the members.

I was sort of curious. I don't know if Mr. Foster had a chance to—we were kind of speculating over here as to whether there's value in doing the kind of marking of all of these different sources to determine whether there was at some point sort of one general dispersion so that there is a relationship between potential life that we might detect one place and another, and so I don't know if that kind of work is going on. And I wondered, Dr. Lunine, if you could speak to that.

Dr. LUNINE. Sure. I'd be happy to. I assume you're talking about in our solar system?

Ms. EDWARDS. Yes.

Dr. LUNINE. So there's been quite a lot of work done of course to understand how frequently material has been exchanged between the Earth and Mars, as I alluded to, but also for Europa, is it possible to get material from Europa to the Earth and vice versa? And then Enceladus and Titan. And the answer is that the farther out you go, the less likely it is. So the most recent studies that have been done, which are all computer models, say that the chance of cross contamination between the Saturn system and the Earth is very, very small, and the chance of contamination between Europa and the Earth is a little bit higher but still relatively small.

So one of the advantages of going to the outer solar system, in addition to exploring Mars, is that we may be going to habitable environments which have not been contaminated by either the Earth or Mars, and so if we find life there or the signs of life, we have somewhat higher assurance that that life had an independent origin of life on Earth, which of course is one of the important questions. Could life have begun more than once in our own solar system? And that's one of the attractions of going to the outer solar system.

Ms. EDWARDS. So then that leads me to another question. And, Dr. Lunine and Dr. Bean, in a 2007 National Academies report called "The Limits of Organic Life in Planetary Systems," there was a caution against searching for a model of life that's based on the model that we know here on Earth and a conclusion that life is possible in forms different from those on Earth. And so I wonder if you could talk to me about the recommendations that came from the report to further inform investigations to detect and identify possible forms of life and other planetary environments?

And I think, Dr. Lunine, in your testimony, in your prepared statement you asked whether the seas of Titan should be included in our search for life because of the Titan's use of methane as a working fluid in place of water? So I guess my question is to what extent would missions to Titan and other potentially habitable environments be able to investigate habitats of life forms that are different—that may be different from those on Earth?

Dr. LUNINE. So the 2007 report came out very strongly in favor, as you noted, of looking in environments that had the general conditions for habitability: energy, liquid, organic molecules, and that if in fact those environments were found not to have a form of life, that that would tell us that there's something indeed very special about liquid water. And so that was I think one of the recommendations, as I recall, of that report.

The challenge of course is how to look for biochemistry in a methane/ethane liquid. What do we actually look for? There's no guideline that terrestrial biology gives us except for the guideline that life will be very selective in the chemical compound that it uses for catalysts, for building structures, and so on. And so therefore, if we go back to Titan, for example, with a boat or a submarine or whatever to explore these seas, if we find that the organic molecules in the seas are just like what's in the atmosphere, you know, basically everything, that's not going to be very promising in terms of life. But if there's a suite of particular molecules and structures that are made over and over again, then that might suggest that if not life itself, at least a chemical evolution toward life is happening in those seas. Beyond that, it's hard to say very much because we have our one example of life on the Earth.

Now, just very briefly, in places like Enceladus and Europa, which have very Earth-like environments, we would expect that many of the basic molecules that terrestrial life uses like amino acids, which are abundant in the cosmos, that we would see that in life in those environments.

Ms. EDWARDS. Dr. Bean, in the time remaining.

Dr. BEAN. Right. In the context of the search for life on extrasolar planets, astronomy, my field, is a very discovery-driven field. We want to build space telescopes and instruments that are designed to be able to answer a question and we inform, you know, the design of those instruments with what we know about on Earth. But we also know that we're going to find unexpected things and so we want to have as flexible of instruments as possible and we want to make as complete a characterization of these planets as we can.

Just to give you an example, the Hubble Space Telescope and the Spitzer Space Telescopes were never designed to look in the atmospheres of extrasolar planets, but that has become one of the most impactful things that those telescopes have done just because they were built with a suite of instruments that were very flexible. And so we have to benchmark our design for these instruments based on what we know, and what we know is limits of the Earth. But we also want to remain open-minded and flexible and do this complete characterization of the planets to try to answer this question in as holistic away as possible.

Ms. EDWARDS. And I've greatly exceeded my time.

Chairman SMITH. Thank you, Ms. Edwards.

The gentleman from Colorado is recognized for his questions not with trepidation but with curiosity and expectation because I'm never sure where he's going to go with his questions. But he is recognized.

Mr. PERLMUTTER. And, Mr. Chairman and to the Ranking Member, I've served on a lot of committees in the Congress, and this Committee is by far the most exciting, stimulating, energizing committee in the Congress. And as I'm sitting down here and looking up at the top row and reading Tennyson, "For I dipped into the future, far as human eye could see, saw the vision of the world, and all the wonder that would be." Listening to you all, that's what this is about. This is—this gives me goose bumps. The versatility of your instruments or your minds to say, you know what, this was really intended to do that but we could use it for this. And I just enjoy this Committee.

So—and Dr. Bera talked about the challenge and the desire of all of us to explore. I mean I have some differences with the Chairman on prioritizing and actually funding because I see what you all do and your research and your service to be investments in the future, and that will pay for a long time to come. And I don't think it's a zero-sum game pitting the astronomers against the physicists and all that stuff. And I don't think the Chairman does either, but I really would like to see us move forward obviously with the Orion project and get humans to Mars.

And with that, I'm going to yield to my friend from Maryland for her questions.

Ms. EDWARDS. And I thank the gentleman from Colorado. We pulled a fast one on the Chairman there.

Dr. Stofan, I just had one question about how you're planning to use the Astrobiology Roadmap that's going to be released later this year and a year later than initially thought. Will it be a major vehicle that NASA is going to use to establish priority and—priorities? And then what kind of challenges did the agency face that caused a one-year delay to the issuance of the roadmap?

Dr. STOFAN. The Astrobiology Roadmap that again will come out shortly, the reason that it's taken longer is because this science is evolving so rapidly and how the scientific community looks at it, bringing in all these multiple disciplines that want to have a voice in astrobiology because you might have thought ten years ago if you're a heliophysicist that nothing you do has anything to do with astrobiology. All of a sudden you say, wait, I can actually contribute. And so that's been—the reason for the delay of the roadmap is we've just been trying to get the best science from the scientific community, get it properly reviewed, and get it out as soon as we can. And so we're happy that it's done and it's about ready to go.

How we use those roadmaps is—definitely comes in several different ways. Basically, when anybody then proposes to NASA, whether it's to do research, to do a mission, they then say here's how my mission that I'm proposing maybe to a competitive line at

NASA. Here's how I'm consistent with the goals of what the community is saying. And then we can use that at NASA and say is this really high priority? Because we look to the community through these community roadmaps, through the decadal process to say what is the best science, what's the latest science, the most up-to-date science, and then how can we use that to inform our decision-making?

Ms. EDWARDS. So just really quickly, is there a plan to have the National Academies review the roadmap as well?

Dr. STOFAN. I don't know that. I can take that for the record.

Ms. EDWARDS. All right. And with that, I will yield back to the gentleman from Colorado and just say I am—I do get a little bit concerned with these, you know, constant discoveries which are really great and we find incredibly fascinating, that the public then becomes numb to it in a way that would harm us in terms of making sure that you have the resources that you need.

And with that, I yield back to the gentleman——

Mr. PERLMUTTER. Thanks.

Ms. EDWARDS. —from Colorado.

Mr. PERLMUTTER. And to the Chairman and the Ranking Member, the thing that I enjoy about this is we are so—looking so forward and towards the future. And tonight, I don't know if you talked about The Martian or not, but the thing that is so fun about that book, one, he's a wise guy; and two, in that book, it's about problem-solving, whether it's math or engineering or physics or biology.

And that's what is so enjoyable about this Committee and about the panels that come and speak to us because I see you all as looking to the future and solving problems, and I just thank you for that. And I thank the Chairman and the Ranking Member for this Committee because it gives me energy every time I come in here.

Chairman SMITH. Thank you, Mr. Perlmutter. You actually beat me in quoting Alfred Lord Tennyson because I was going to end by doing that. However, just to add one more tidbit of information here, this quote that you see behind us on the wall is from a poem called Locksley Hall and of course written by Alfred Lord Tennyson who lived from 1809 to 1892. I have the entire poem right here. It's multiple pages but that is a wonderful excerpt of it.

That brings us to the end of our hearing, which was obviously informative and exciting to all of us. And let me just simply add that when we think that we're somehow limited in what we might explore or what we might detect elsewhere in the cosmos, I think it's helpful to remember that we here in the United States went from the Wright Brothers to Apollo in 66 years. In 1903 we had the Wright Brothers. We had two guys flying a contraption a couple hundred feet, 20 feet above the ground. Sixty-six years later, we had 12 people walking on the Moon over several years. And any country that can do that can certainly continue to explore and learn from that exploration, and who knows, maybe even detect some form of life elsewhere.

So thank you all for being here, most enjoyable hearing, and I thank the Members who are here as well. And we stand adjourned.

[Whereupon, at 11:42 a.m., the Committee was adjourned.]

Appendix I

ANSWERS TO POST-HEARING QUESTIONS

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Ellen Stofan

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Astrobiology and the Search for Life Beyond Earth in the Next Decade"

Dr. Ellen Stofan, Chief Scientist, NASA

Questions submitted by Rep. Lamar Smith, Chairman

QUESTION 1:

What are the criteria NASA uses to verify a claim that life has been discovered beyond Earth?

a. Is this criteria accepted by the broader astrobiology community?

ANSWER 1 & 1a:

Carl Sagan proposed and NASA has adopted a working definition for life: a "self-sustaining chemical system capable of Darwinian evolution." Beyond this, the NASA Astrobiology Program does not employ a more formal definition. In searching for signatures of life in extreme environments on Earth and on other worlds, some basic behaviors of materials are investigated, including their ability to metabolize, evolve, and reproduce. Defining life as we know it, much less life as we do not know it, is so difficult that concepts of life are frequently discussed in workshops and working groups within the astrobiology community.

QUESTION 2:

How does NASA manage education and public outreach related to astrobiology?

a. Are there any anticipated changes to astrobiology education and public outreach strategy?

ANSWER 2 & 2a:

Recently, NASA restructured the Science Mission Directorate's educational and public outreach functions. For communications (including news, social media, and public outreach), efforts are more coordinated to increase efficiencies. SMD's outreach efforts include Famelab, astrobiology-related newsletters, websites, and social media sites. For education, SMD has restructured its entire portfolio from a missions-related structure to science disciplines-related structure. This revised structure aligns more closely with how science is taught in formal and out-of-school settings. All effort was competed and selections were announced on September 25, 2015. Within the selections, which are currently being negotiated leading to awards in early January, astrobiology content will be optimized in online courses and other out-of-school learning environments.

In addition, NASA often receives emails from young people around the world, mostly high school students and undergraduates, who request advice on how to

pursue astrobiology as a career. As such, we 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. Links to existing university programs/hubs, astrobiology related newsletters, etc. are also provided so they can become involved with the community right away. These opportunities and education resources remain as part of the current Education and Public Outreach efforts and can be found at:
http://astrobiology.nasa.gov/careers/astrobiology-career-path-suggestions/
http://astrobiology.nasa.gov/education-resources/

QUESTION 3:

Four hundred years ago, the astronomer Galileo's discovery of Jupiter's four large moons forever changed humanity's view of the universe, helping to bring about the understanding that Earth was not the center of all motion. Today one of these Galilean moons, Europa, could again revolutionize science and our sense of place, for hidden beneath Europa's icy surface is perhaps the most promising place to look for present-day environments that are suitable for life.

a. What makes Europa such a good candidate for the search for life?
b. What steps is NASA taking to search for life on Europa?
    i. Why isn't NASA planning a probe to go under Europa's surface ice and physically interact with its subsurface ocean?
    ii. What amount of funding does NASA need to conduct a Europa exploration mission that includes penetrating its icy surface and physically interacting with its subsurface ocean?

ANSWER 3a – 3b(ii):

Europa is considered one of the most intriguing and astrobiologically promising bodies in our solar system. The compelling evidence of a liquid water ocean beneath its icy crust, that has access to the interior core and energy exchange through the ice shell, creates the ocean's potential for extant life. Penetrating the ice crust to directly access the ocean presents a serious challenge, and at this time there are no planned missions to do so. In fact, the thickness (and other basic parameters) of the ice crust is unknown but expected to be tens of miles thick. One of the goals of the Europa multiple flyby mission is to determine that thickness and other properties of the ice crust, and this knowledge could potentially help us design a vehicle that someday could penetrate the crust of ocean worlds such as Europa. Because of the scientific value coupled with the difficulty of penetrating the ice crust to reach the ocean, NASA already has early technology development efforts underway to develop methods and technology to eventually be able to penetrate the ice and directly sample the oceans that characterize the ocean worlds in our solar system. These technologies are currently immature but potentially promising. Mission costs are unknown but likely significant.

QUESTION 4:

NASA recently announced selection of nine instruments for a mission to Jupiter's moon Europa to investigate whether Europa could harbor conditions suitable for life.

a. Are any of these instruments able to detect life?
   i. If not, why isn't such an instrument included?

ANSWER 4a & 4a(i):

The Europa mission does not include a "life detection" instrument – such a device or technology has yet to be developed or invented. The scientific community is working towards defining instrumentation that would progressively increase the ability to detect life. When some consensus can be reached to identify the types of measurements needed to detect life, instruments can then begin development. The instruments selected for the currently planned mission to Europa are designed to determine habitability, which is the first and necessary step toward life detection. However, some of the selected instruments also have the ability to detect biosignatures, which are materials that provide evidence that life could be present.

QUESTION 5:

How will NASA determine, unambiguously, if Europa has living biological life?

ANSWER 5:

The unambiguous detection of life is a surprisingly difficult measurement. There is currently no single measurement or set of measurements accepted by the astrobiology community that would *unambiguously* signal the presence of life.

QUESTION 6:

The House of Representatives recently passed a FY 2016 appropriations act which provides an additional $110M dollars over the Administration's request for Europa accounts. NASA has not yet provided a date for a mission to Europa to launch. When do you expect NASA's mission to Europa to launch?

ANSWER 6:

Please refer to the NASA Planetary Science section of the President's FY 2017 Budget for additional details on the Europa mission.

QUESTION 7:

What proportion of astrobiology research in the United States is funded directly or indirectly by NASA?

ANSWER 7:

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 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 (e.g. J. Craig Venter Institute (JCVI), Simon Foundation, Templeton Foundation, Breakthrough Prize Foundation).

QUESTION 8:

How much money has NASA allocated to support astrobiology research in its FY 2015 Research Opportunities in Space and Earth Sciences (ROSES)? What percentage of ROSES funding is allocated to astrobiology?

ANSWER 8:

Approximately $57 million is allocated to astrobiology research, which represents 25.5 percent of the Planetary Science Research and Analysis (R&A) budget.

QUESTION 9:

NASA current plans for a mission to Europa are for a spacecraft, called the "Europa Clipper" which will conduct flybys of Europa. This concept does not include exploration of the subsurface ocean. What would be the scientific value of physically exploring the subsurface ocean of Europa, as opposed to remotely sensing it with an orbiting satellite?

ANSWER 9:

The scientific value of exploring the subsurface ocean is potentially very high but technically daunting and expensive. However, the ocean can be explored without penetrating the ice crust then placing a vehicle in the ocean. The current Europa multiple-flyby mission concept can do an outstanding job of understanding Europa's potential habitability, through investigations the satellite's ice shell, ocean, geology, and composition. Some of the science instruments will perform remote sensing, while others will perform in situ investigations of the satellite's thin atmosphere and potential plumes. These plumes could be lofting material from the ocean high into space, allowing us to directly sample the ocean without drilling through tens of kilometers of ice. It is also likely that some of the strange geology on Europa is the result of material from the ocean being dredged up to the surface. Like the plumes, this surface material may provide a sample of the ocean without requiring us to penetrate the ice crust. The remote sensing instruments on the flyby spacecraft will be able to see these materials that are exposed on the surface of Europa, where they have been processed to various degrees by radiation (i.e., by high-energy particles that hit Europa's surface). The in situ instruments will measure ice, dust, and plasma particles that have been knocked off of Europa, and these processed materials are indicative of the purer material that sits on and just beneath Europa's surface. Complex organic materials can be measured this way, but they will experience some degree of processing by radiation and by the speed of the spacecraft upon sampling in situ.

QUESTION 10:

Water is thought to exist as liquid beneath the surface of icy planetary bodies within our solar system, such as Mars, Europa, Enceladus, and Ganymede. These frozen moons and planetoids may have warm underground oceans with habitable environments.

a. How are past and current NASA planetary science missions informing the search for life on icy bodies within our solar system?
b. What missions is NASA planning to explore subsurface oceans?
c. Are there any planned missions which will physical penetrate and interact with subsurface oceans? If not, why?
d. What are the benefits of conducting a science mission that physically penetrates into and/or interacts with the subsurface oceans?
e. What are the limitations the science which can be achieved by remotely sensing subsurface oceans?

ANSWER 10a-e:

Many of NASA's Planetary Science missions in recent decades have included astrobiology-focused investigations, with the idea of informing the search for life on other planetary bodies both icy and rocky. The rather new concept of icy bodies as ocean worlds that could provide a habitable environment for life is less than two decades old. Since their discovery, however, NASA has been investigating whether these bodies could harbor conditions suitable for life, utilizing missions such as Cassini's recent flyby of Enceladus' plume and the continued development of a Europa mission that would conduct detailed exploration of Jupiter's moon.

At this time, there are no planned missions that will physically penetrate and interact with subsurface oceans. Penetrating the ice shells on ocean worlds is a daunting task: the ice shells are an unknown thickness, have an unknown structure and composition, and at the temperature of these bodies, the ice is similar to granite. The potential benefits of a mission that interacts with the oceans are aptly demonstrated by oceanographic exploration on Earth, and NASA is beginning to work more with NOAA to learn how it conducts such exploration.

However, experience has shown that tremendous science can be achieved without the cost and uncertainty of penetrating the oceans. Just a few flybys of Europa by the Galileo spacecraft discovered the first extraterrestrial ocean and spawned the concept of ocean worlds beyond Earth. Cassini's flybys of Enceladus and its plumes have discovered not only another global ocean there but have discovered evidence of hydrothermal activity on the ocean floor.

Neither of these missions were designed with the intent to explore an ocean world – ocean worlds were beyond imagining at the time the missions were conceived - yet the missions made amazing discoveries. The Europa multiple flyby mission is explicitly designed as an ocean worlds mission that will not only return tremendous science but is also a necessary step before penetrating the icy crust and entering the ocean. As mentioned in the answer to question 3, NASA is already investing in technologies to penetrate and sample the oceans on ocean worlds such as Europa.

QUESTION 11:

What other countries are investing in and conducting astrobiology research? And why?

a. In what areas of astrobiology research are other countries becoming leaders? And why?

ANSWER 11 & 11a:

Several European countries invest in Astrobiology research. In some cases, these investments are linked to the countries' space agency goals (Italy, France) and in other cases, these investments are linked to historical areas of interest and geography (Spain, Norway). European countries tend to focus on life in extreme environments, prebiotic chemistry, and space biology. Meanwhile, Japan has launched a new initiative in origins of life research that is quickly becoming a leading research area in this effort. In addition to substantial financial resources going towards this effort, their initiative focuses on globalization. Their model brings experts from around the globe, including U.S. researchers, together to focus on the most compelling questions in origin of life research. Japan has also had a long-standing program in analog research. Canada is very active in analog research, while Chile and Australia also have active astrobiology programs.

QUESTION 12:

What international partnerships, if any, does NASA have in astrobiology sciences?

a. How can NASA better leverage international cooperation to advance of astrobiology research?

ANSWER 12 & 12a:

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 NASA 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 U.S. researchers to unique analog sites and participation in field campaigns to analog environments and inclusion of U.S. scientists on non-U.S. missions and *vice* *versa*. Field sites for astrobiology research have ranged from Antarctica to Alaska, Australia, Canada, Chile, 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.

QUESTION 13:

It is reported that the surface of Mars is not habitable to biological life, in part due to the lack of a Martian magnetic field to protect from solar radiation and in part due to perchlorates.

a. How do planned and future NASA missions to Mars address this challenge?
b. Where is evidence of life most likely to be found on Mars?

ANSWER 13a & 13b:

The radiation environment at Mars is indeed more severe than at Earth. To better understand this, our rovers carry radiation sensors to characterize the surface radiation, which varies in intensity depending upon the shielding provided by local landforms. Perchlorates (chlorine- and oxygen-based salts that are similar to bleach) do not necessarily rule out the presence of life. They lower the freezing point of water and, in some Earth bacteria, have been found to be involved in their metabolic processes.

On Earth, all forms of life need water to survive. It is likely that if life ever evolved on Mars, it did so in the presence of a long-standing supply of water. On Mars, we are searching for evidence of life in areas where liquid water was once stable, and below the surface where it still might exist today. In addition to liquid water, life also needs energy. Therefore, future missions will also be on the lookout for energy sources other than sunlight. Chemical and geothermal energy, for example, are alternate energy sources used by life forms on Earth and may have played a role in supporting microbial life in the protective environment of the Martian subsurface.

QUESTION 14:

What steps is NASA taking to protect against the transfer of viable organisms from Earth to celestial bodies which may harbor life?

ANSWER 14:

NASA planetary protection policy is intended to prevent the biological or organic contamination of other solar system bodies (forward contamination) and protect the Earth against possible hazards in material returned to Earth from other worlds (backward contamination). For missions going to locations where Earth life could thrive (e.g., Mars, Europa and Enceladus), constraints would include restrictions on mission operations, control of the materials used to construct the spacecraft, cleanroom processing of spacecraft, enumeration and reduction of the number of microbes living on a spacecraft, and documentation of the spacecraft operations and disposition at the end of a mission. Missions intended to collect and bring samples of material that could host native life back to Earth are required to limit terrestrial contamination that could be introduced into samples for return, and provide comprehensive documentation including identification of potential microbial contaminants, as part of the Earth Safety Analysis and to support assessment protocols required to be performed, under strict containment, after return.

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Astrobiology and the Search for Life Beyond Earth in the Next Decade"

Dr. Ellen Stofan, Chief Scientist, NASA

Questions submitted by Rep. Eddie Bernice Johnson, Ranking Member

QUESTION 1:

How will the NASA Nexus for Exoplanet System Science (NExSS) initiative enhance the search for life on planets outside our solar system? When do you anticipate receiving the initial results from this initiative?

ANSWER 1:

Nexus for Exoplanet System Science, or "NExSS", is a research coordination network that will leverage current NASA investments in research in many fields in order to understand how planetary processes lead to potentially habitable exoplanets, as well as how the planet stars and neighbor planets interact to support life. With the discovery of more than 1,000 exoplanets to date, scientists are developing ways to confirm the habitability of these worlds and search for biosignatures, or signs of life. The key to this effort is understanding how biology interacts with the atmosphere, geology, oceans, and interior of a planet, and how these interactions are affected by the host star. This "system science" approach will help scientists better understand how to look for life on exoplanets. NExSS will tap into the collective expertise from each of the science communities supported by NASA's Science Mission Directorate.

- **Earth scientists** develop a systems science approach by studying our home planet.
- **Planetary scientists** apply systems science to a wide variety of worlds within our solar system.
- **Heliophysicists** add another layer to this systems science approach, looking in detail at how the Sun interacts with orbiting planets.
- **Astrophysicists** provide the expertise in observations and data on the exoplanets and host stars for the application of this systems science framework.

NExSS will bring together these prominent research communities in an unprecedented collaboration, to share their perspectives, research results, and approaches in the pursuit of one of humanity's deepest questions: are we alone? The team will help classify the diversity of worlds being discovered, understand the potential habitability of these worlds, and develop tools and technologies needed in the search for life beyond Earth.

In the next 2 years, NExSS will organize and lead workshops in order to produce a series of white papers that document the community's consensus on the current state of the field, the challenges researchers and engineers need to overcome to move the field forward, and the work that needs to be done to overcome those challenges. These white papers will inform and serve as a guide to the medium-to-long term research that moves the field forward. They will also serve as an input to Science Definition teams that will be studying our capability to fly missions that can search for signs of habitability and life on exoplanets, and which would also serve as inputs for the next Planetary Science Decadal Survey.

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Astrobiology and the Search for Life Beyond Earth in the Next Decade"

Dr. Ellen Stofan, Chief Scientist, NASA

Questions submitted by Rep. Bill Foster, Member

QUESTION 1:

Could you provide a rough estimate of the cost-per-sample of a sample collected and analyzed by a human on Mars versus a sample collected and analyzed by a machine?

ANSWER 1:

The costs associated with sending humans to Mars are still being evaluated by NASA. It is important to note that beyond conducting groundbreaking science to expand our knowledge of Mars (including the analysis of Mars rock and soil samples), NASA is implementing an integrated human and robotic exploration strategy to expand human presence into the solar system, including conducting human missions to Mars. Mars is the horizon goal for pioneering space; it is the next tangible frontier for expanding human presence, and the journey to Mars requires advanced human and robotic partnerships not imagined at the time of Apollo.

NASA and our partners are already at Mars, operating with highly effective robotic emissaries in orbit and on the surface. The Agency will build upon its increasingly advanced fleet of Mars robotic explorers that have dramatically improved our scientific knowledge and helped pave the way for astronauts to travel there. Our robotic science scouts at Mars have found valuable resources for sustaining human pioneers, such as water ice just below the surface. These scouts have shown that Mars' geological evolution and climate cycles were comparable to Earth's, and that at one time, Mars had conditions suitable for microbial life. Along with conducting their high-priority science objectives, it is anticipated that robotic pathfinders will investigate and map destinations prior to human missions, collect surface samples, characterize potential landing sites, and test technologies necessary for future robotic and human destination systems. Over the next decade, NASA will rely on robotic pathfinders to help select human-accessible landing sites, pre-emplace infrastructure, and inform the design of human destination systems. In addition, the Agency's robotic missions will help test some of the advanced technologies that will be required for human missions to Mars.

It is important to note that in this journey, the human and robotic explorers will play a complementary role. While robotic missions will serve as science and technology pathfinders for crewed missions to Mars, astronauts on the surface of the planet will be able to expand our knowledge and inform mission planning for further robotic exploration. Astronauts will be able to collect a greater volume and diversity of rock and soil samples than would be possible using robots alone. In addition, as was the case with the rock samples collected during the Apollo missions to the Moon, astronauts on the Martian surface will be able to make *in situ* judgments about samples to be retrieved, and will be able to record the context in which those samples were discovered. Additionally, we expect astronauts on Mars to be able to analyze orders of magnitude more samples than get returned. This will enhance the scientific quality of the samples that are selected to be returned to Earth. Continued robotic (and potentially tele-robotic) exploration of Mars will ensure that areas of the planet not as readily accessible to human crews do not go unexplored.

Material requested for the record on page 44, line 945, by Representative Babin during the September 29, 2015, hearing at which Dr. Ellen Stofan testified.

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 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 (e.g. J. Craig Venter Institute (JCVI), Simon Foundation, Templeton Foundation, Breakthrough Prize Foundation).

Material requested for the record on page 53, line 1162, by Representative Abraham during the September 29, 2015, hearing at which Dr, Ellen Stofan testified.

No, NASA is not a regulatory agency.

Material requested for the record on page 78, line 1798, by Representative Edwards during the September 29, 2015, hearing at which Dr, Ellen Stofan testified.

Yes, the astrobiology strategy was presented to the National Academy of Science's Committee on Astrobiology and Planetary Sciences on September 17, 2015, for the committee members to review and comment.

Responses by Dr. Jonathan Lunine

Corrections to the transcript:

Line 441: Change "with modern" to "but with modern"
Line 1385. Change "2 billion" to "½ billion".

Questions from Chairman Smith:

Questions submitted by Rep. Lamar Smith, Chairman

1. **What do you expect the next major scientific breakthroughs in astrobiology to be?**
2. **Is there anything NASA or the U.S. Government can do to better foster private sector philanthropy in support of astrobiology research?**
3. **NASA current plans for a mission to Europa are for a spacecraft, called the "Europa Clipper" which will conduct flybys of Europa. This concept does not include exploration of the subsurface ocean. What would be the scientific value of physically exploring the subsurface ocean of Europa, as opposed to remotely sensing it with an orbiting satellite?**
4. **What future missions should NASA prioritize to explore subsurface oceans?**

1. Response: Let me define "major breakthrough" as being comparable to the detection of the first planets around other stars or the discovery the RNA can catalyze some biological processes and hence serve a dual role in primitive life. Given that definition, the next major breakthrough will be finding evidence for life elsewhere in the solar system. I cannot say whether it will be extinct life or life that is alive today, but in either case the breakthrough will consist of multiple lines of chemical or physical evidence for biological processes, rather than viable organisms themselves. Such a breakthrough would be possible if and only if the nation pursues a vigorous program of exploration of Mars and the ocean worlds of the outer solar system in the next two decades.

2. Response: Private philanthropy is most effective in funding ground-based facilities from which results can be obtained in a relatively short amount of time and which might not be attractive for federal funding—hence, funding for SETI hardware, for certain types of ground-based telescopes, and for laboratories where the techniques of life detection can be honed for eventual application to the search for life on other bodies in our solar system. In many cases the most effective conduit for such efforts is through the nation's universities, but donors might need to see that their generous provision of funds will connect to a larger purpose—namely that of determining whether we are alone in the cosmos. NASA and the U.S. Government can help by providing a clear and coherent picture of how spaceflight activities connect with smaller scale ground-based and laboratory-based efforts at non-federal institutions including universities.

3. Response: The value of exploring the subsurface ocean of Europa lies in finding compelling indirect evidence for life through chemical clues that biology is happening in the ocean, or direct evidence in the form of organisms that can be observed, cultured, and studied. It is possible that finding the chemical clues to life will be possible without entering the ocean, through analysis of plumes should they exist at Europa. However, (in contrast to Enceladus) evidence for the Europan plumes is circumstantial at the moment and, even if they exist, we don't know enough about their characteristics to sample them. Before we plan a mission to penetrate into the ocean of Europa we must understand how thick the crust is, where the ocean might possibly be exposed periodically as tidal stresses act on surface fractures, search for deposits of organic molecules near fractures to verify that the ocean contains life's essential ingredients, and sample the plume or plumes if present. These are the main goals of what is now the Europa Multiple Flyby Mission (formerly Europa Clipper), and completing them is an essential prerequisite—in my opinion—to sending landers or penetrators onto the surface or into the Europan ocean.

4. Response: (What follows is my personal view, but one that is based on decades of participation in NASA and ESA planetary exploration missions.) The presence of three outer solar system worlds with known subsurface oceans, surface seas of methane and other hydrocarbons in the case of Titan, and (in Enceladus' case) strong evidence for hydrothermal systems at its ocean's base, represents a remarkable exploration opportunity for NASA. The agency should tailor the exploration of each moon to what we know about them ...which is different in each case. Enceladus' plume is well characterized; Cassini has flown through it multiple times ingesting and analyzing samples. We know from these analyses that the ocean beneath Enceladus' surface is salty, charged with carbon-bearing molecules, and very likely posses at its rocky base a hydrothermal system. The next step for this moon is to return with more advanced instrumentation to sample the plume and look for the signatures of biology. *We do not need to penetrate the thick crust to search for biomarkers in Enceladus; we need only sample the plume.* This might be done for approximately the cost of a Discovery-class mission. For Titan, landing on the surface seas to sample them directly...to sail the only open seas in the solar system beyond Earth and explore what is in them—should include a search for possible exotic forms of life. Such a Titan "boat" will likely require a communications relay spacecraft in Saturn orbit and hence a New Frontiers-class cost tag. For Europa, NASA is doing the right thing with the Europa Multiple Flyby flagship mission, and the goal should be to launch it as soon as possible, use the data it obtains to understand where and how to land in a future mission to sample pristine ocean material, and in turn use that knowledge to implement Europan ocean exploration on a more ambitious, follow-on mission.

Questions from the ranking member:

Questions submitted by Rep. Eddie Bernice Johnson, Ranking Member

1. **In your prepared statement, you state that "direct sampling" is the way to "tease out" any secrets of life that may be present on bodies that may harbor or may have once harbored microbial life. With respect to Europa, you also state that "we do not know how to access oceanic samples to make the determination". Others have previously testified that going all the way to Europa and not touching its surface would be a lost opportunity.**
    a. **Are we ready to pursue direct sampling on Europa, Mars, Titan, and Enceladus? If not, what precursor activities are needed?**
    b. **What is your perspective on whether adding a lander should be considered for a Europa mission?**

1a. Response: Our ability to directly sample surfaces or subsurfaces of planets and moons depends on our knowledge of each particular body and the specific conditions present on each. We know a great deal about the Martian surface and, through the Mars Exploration Rovers and Curiosity Rover, we have undertaken and are undertaking extensive direct sampling of multiple sites on the Martian surface. As I noted in my testimony, this historic exploration combined with orbital data have set the stage for a search for evidence of life on Mars, and the upcoming Mars2020 Rover has instruments that will be very useful in this effort.

Saturn's large moon Titan has been throughly mapped by Cassini Orbiter instruments and one surface site was briefly studied directly by the European Huygens probe. Cassini's discovery and remote sounding of the large seas around the north pole of Titan make these vast bodies of methane-ethane liquid an attractive target for direct surface sampling (Huygens landed many thousands of kilometers away from these seas, before Cassini discovered them).. Because the seas are not made of water, but rather of hydrocarbons, they may not contain life or may contain an extremely exotic form of life not encountered on Earth, but it will take a mission to float on or even sail within these seas to find the answer. Cassini provided the necessary precursor information to design such a mission today.

The plume of Saturn's moon Enceladus is well characterized; Cassini has flown through it multiple times ingesting and analyzing samples, and we know from these analyses that the ocean beneath Enceladus' surface is salty, charged with carbon-bearing (organic) molecules, and very likely posses a hydrothermal system at its rocky base. *We do not need to penetrate the thick crust to search for biomarkers on Enceladus.* Instead, to search for signs of life requires doing what Cassini has demonstrated multiple times—fly through and analyze the plume—but with modern instruments that have the sensitivity and power to detect biologically produced molecules. The instruments on Cassini were designed a quarter of a century ago and do not have the resolving power to do this. Hence a mission to Enceladus following on from Cassini is required, and we have the necessary data from Cassini to design and fly it.

Even though we knew of the ocean of Jupiter's moon Europa before we knew of oceans in Enceladus and Titan, paradoxically we know less about it. This is a consequence of problems with the Galileo orbiter that explored Europa in the late 1990's—the main communications antenna did not unfold, and some of the mission's instruments (built in the early 1980's) were adversely affected by the intense radiation environment around Europa. And so, before an extensive campaign to land on the surface or even penetrate to the ocean can be considered, we must go back with advanced instruments to measure the thickness of the ice above the ocean, determine if the fractures imaged by Galileo periodically open to expose ocean water to the surface, and search for organic molecules on the surface. Also, if Europa has plumes as hinted by Hubble data, we should try to find their locations and attempt sampling by flying through them. The Europa Multiple Flyby Mission (previously called Clipper) is supremely suited to make these measurement with its well-selected, modern suite of instruments. This mission must fly as soon as is feasible as it will pave the way for surface exploration.

1b. Response: Again, this is my personal view but one informed by involvement in Europa mission studies since 1999. A lander on the Europa Multiple Flyby Mission (EMFM) is premature. Such a lander would not get down into the ocean, and its ability to land and operate on the surface will be a function of the nature of the surface—which we do not know well at the moment, but will from EMFM. Once we get the required information from EMFM (see response to 1a), we can plan the next step...should it be to land near one of the fractures, to try to drop directly into the ocean, or land somewhere else on the surface? The results of EMFM will give us critical data to properly design a future landed mission. To those who argue that not touching the surface will be a lost opportunity, I would respond by pointing to the large potential cost of such a lander, which has uncertain consequences for the funding and launch date of EMFM itself. For those of us who want to know whether there is life within the ocean of Europa, a launch of EMFM as early as possible is the most important step that the space agency can take.

Responses by Dr. Jacob Bean,
HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Astrobiology and the Search for Life Beyond Earth in the Next Decade"

Dr. Jacob Bean, Assistant Professor, Department of Astronomy and Astrophysics, University of Chicago

Questions submitted by Rep. Lamar Smith, Chairman

1. How much of NASA's current astrobiology program focuses on the study and characterization of exoplanets?
    a. How much of that research is dedicated to spectroscopy and the identification of biosignatures in the atmospheres of those planets?

Answer to question #1 and 1a:

I am not in a position to answer this question directly. I can say that I know of no efforts in the exoplanet community currently focused on measuring biosignatures because that is out of reach of existing instruments. All biosignature research at the present is either theoretical or in the area of instrument development.

2. What are the major differences between government-funded exoplanet research and exoplanet research conducted by the private sector? Does it carry the same weight in the scientific community?

Answer to question #2:

There is little difference in the exoplanet research that I know of funded by federal sources and the private sector. If there are any differences it may be that private funding enables slightly more risky research. Most of the exoplanet research that I know of being done with private funds is perfectly aligned with mainstream scientific thinking and not in any way more controversial. That is, this is research that is in principle fundable by federal sources, but private sources of funding were sought out due to the limited federal funding available.

Research in the field of exoplanets is not judged based on the funding source. Only the intrinsic scientific merit matters.

However, with that said, federal funding for this topic vastly exceeds private investment. The situation might be different if the reverse were true.

3. The Space Telescope Science Institute indicated that a telescope larger than JWST is needed to detect biosignatures from terrestrial-like exoplanets. They also indicated that a heavy launch vehicle such as the Space Launch System is needed to launch a spacecraft of this size. How does the development of the SLS enable future programs to discover and study exoplanets?

There are three main limitations for current rockets to putting large telescopes in space: the size of the fairing they can accomodate, the weight of the payload they can carry, and what distance from Earth they can deliver the payload.

Of these issues the one I am most familiar with for exoplanet telescopes is the one of size. Direct imaging of exoplanets is better enabled with so-called 'monolithic' primary mirrors. That is, mirrors that are not segmented like the JWST primary mirror. The reason is that light is bent by the gaps between mirror segments in ways that make suppressing the light from planet host stars much more difficult. Suppressing the blinding glare of planet host stars is the primary technical challenge for taking spectra of Earth-like planets to look for biosignature gasses.

If the telescope mirror isn't segmented then it can't be folded in to a smaller volume for launch. Therefore, the fairing housing the telescope during the launch has to be at least as big as the full size of the mirror.

It is my understanding that the limitations of current launch vehicles restrict the maximum telescope size to around four meters. It is likely that a larger telescope, with a size of approximately eight meters, would be needed to make a robust statement about the existence of life on planets in the solar neighborhood. This would require the next generation launch capabilities of the Space Launch System (SLS).

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Astrobiology and the Search for Life Beyond Earth in the Next Decade"

Dr. Jacob Bean, Assistant Professor, Department of Astronomy and Astrophysics, University of Chicago

Questions submitted by Rep. Eddie Bernice Johnson, Ranking Member

1. In your prepared statement, you advocate for a flagship space telescope with next generation optics to detect life on Earth-like planets, a telescope you dub as a Terrestrial Planet Finder or TPF. Because previous TPF concepts were narrowly focused, you indicate that the astrophysics community is currently studying how a TPF program could be used to address a number of topics in astrophysics and planetary science.
    a. If no change occurs to the current budgetary environment, when do you think such a TPF mission could be undertaken and at what cost?

Answer to question #1a:

The astrophysics community is currently working to produce precise answers to these questions. We are considering a range of telescope sizes, which would have a corresponding range of costs and timescales. To give a sense of scale though, most concepts that are being seriously studied have a cost in the neighborhood of $1 to 10 billion. The larger telescopes, which would be on the upper end of that range, would have the best chance for making a robust statement about the existence of life on planets in the solar neighborhood.

It is my understanding that NASA does not have room in the budget for starting a new flagship mission before 2025. Therefore, the timescale for realizing such a mission with no increase in funding is likely beyond the year 2030.

b. Is TPF what you view as the capability needed to achieve the most "bang for the buck" in searching for past or present life beyond Earth?

In short, yes, I do think that a TPF-like mission is needed to achieve the most bang for the buck in searching for life beyond Earth.

The reason I think this is because looking at exoplanets is the only way to make a comprehensive search for complex life and to understand the results. It is a well-posed experiment: find and characterize Earth-like planets and look for signs of life. Knowing about the planets gives us the necessary context for interpreting the existence or non-existence of life. It is guaranteed to yield an interesting answer.

There is value in the alternative of looking for life on other bodies in the Solar System. However, such life, if it exists, will be primitive given how hostile the rest of the Solar System is. Complex life, as we understand it, can only arise and exist on temperate worlds.

There is also value in the alternative of SETI searches for signals from intelligent life. However, I rate the chance of success of these programs as very low, and it is difficult to interpret the null result (a non-detection) in a meaningful way.

c. If not, what investments do you believe will make the greatest contribution to advancing the field of astrobiology and the search for life beyond Earth?

Answer to question #1c:

Not answered because of a positive answer to the above question.

Responses by Dr. Andrew Siemion

Astrobiology and the Search for Life Beyond Earth in the Next Decade

Response to Questions by

Dr. Andrew Siemion

Berkeley SETI Research Center, University of California, Berkeley
ASTRON – Netherlands Institute for Radio Astronomy, Dwingeloo, Netherlands
Radboud University, Nijmegen, Netherlands

from the

Committee on Science, Space and Technology United States House of Representatives
114th United States Congress

November 10, 2015

Questions submitted by Rep. Lamar Smith, Chairman

1. **What do you expect the next major scientific breakthroughs in astrobiology to be?**

   In my opinion, the next major scientific breakthrough in astrobiology will be the discovery of life beyond the Earth, either extant or extinct. It is most likely that we will discover simple extraterrestrial life first, through either in-situ investigations of other bodies in our own solar system or remote sensing of extrasolar planet atmospheres. There is a small probability that our first discovery of extraterrestrial life will be through the detection of technology created by advanced intelligent life.

2. **What are the unique challenges facing radio and optical astronomy research that might not be found in other areas of astrobiology?**

   Using radio and optical telescopes for astrobiology research, including the search for extraterrestrial intelligence, requires measuring electromagnetic radiation from objects that are many light-years away, and inferring physical behavior based on that radiation. The objects being studied cannot be actively probed or subjected to controlled conditions.

3. **Is there a consensus in the SETI community about how to advance the science?**

   The international SETI community is unanimous on these points:

   a. There is an opportunity in the next several decades to undertake powerful new searches for evidence of technologically-capable life beyond the Earth that will be orders of magnitude more sensitive and complete than previous work.

   b. To ensure the longevity of the field of SETI, it is critical to establish a reliable and continuous source of funding for SETI research. Without such a funding source, it is impossible to cultivate the healthy stream of graduate students, postdocs and early-career researchers necessary for a vibrant and flourishing field.

4. **NASA terminated funding for its SETI program in 1993. Should NASA start funding a SETI program again? If so, why? How would it align with current NASA activities?**

In the latest NASA Astrobiology Strategy report, it says "...traditional Search for Extraterrestrial Intelligence (SETI) is not part of astrobiology..." I disagree with this statement. The search for technological life beyond Earth, and the signatures of that technology, so-called "technosignatures," are absolutely part of astrobiology. This includes searches for direct electromagnetic emission from communication or active radar technology as well as searches for in-direct environmental alteration by technology, such as the generation of waste heat by massive energy usage or artificial modification of a planetary atmosphere.

Although it is difficult to predict how common technologically-capable civilizations might be, it is among the most compelling questions in science and indeed in our entire human experience. It is as great a question to ask how commonly life evolves a capacity to inquire about the nature of the universe and volitionally travel between the stars as it is to ask how common life arises at all.

Questions submitted by Rep. Eddie Bernice Johnson, Ranking Member

1. **While private donations have long helped to fund ground-based telescopes, Break- through Listen is a significant donation devoted to the search for extraterrestrial intelligence. Do you anticipate that other private funders will be seeking to either partner in Breakthrough Listen or establish other initiatives related to astrobiology or the search for extraterrestrial intelligence?**

   The search for life beyond the Earth, including the search for intelligent life, is incredibly exciting for scientists, philanthropists and lay people alike. As a result, this field has a long history of attracting private support. I have no doubt that other individuals and foundations will continue to partner with public agencies to help push this field forward.

2. **You were quoted in the Berkeley News as saying," The Breakthrough Listen initiatives is our first opportunity to test the fundamental hypothesis behind modern radio SETI.**

   a. **What is that hypothesis, and does the initiative provide the flexibility to change the hypothesis if needed, and if so, what conditions would lead to such a change?**

      This hypothesis is that there may be advanced extraterrestrial civilizations that have developed radio technology similar to our own, and that this technology could be either intentionally or inadvertently emitting radio signals that we might be able to detect at Earth. The region of the radio spectrum between about 500 MHz and 15 GHz has long been noted as an ideal place to conduct a search for these types of signals, as it represents a naturally "quiet" part of the radio spectrum for terrestrial observation. In Breakthrough Listen, we will conduct the first sensitive and comprehensive search for these types of signals, covering 1 million nearby stars and 100 nearby galaxies.

      Despite being suggested more than 60 years ago, this hypothesis remains a very attractive avenue for exploration in SETI. Radio searches thus represent a key component of Breakthrough Listen. If in the future we make new discoveries or gain new insights that lead us in a different direction, we will absolutely pursue them.

   b. **How will Breakthrough Listen funds be used to acquire the capabilities to survey 10 times more of the sky, cover five times more of the radio spectrum, and work a hundred times faster than any previous program?**

      The key developments leveraged by Breakthrough Listen are the availability of large world-class telescopes, Moore's Law growth in the performance and capabilities of the computing equipment used to perform the search and developments in radio receiver technologies that allow large instantaneous fields-of-view and multiple sky directions to be searched at once.

   c. **Is there a relationship between the UC Berkeley SETI Research Center and the Breakthrough Initiative or is it only at your personal level? Can you share some details on what that relationship entails?**

      The University of California, Berkeley has entered in to a contract with the Breakthrough Prize Foundation to conduct science and engineering work in support of Breakthrough Listen. Several scientists and engineers affiliated with the Berkeley SETI Research Center are involved in this work.

Questions submitted by Rep. Bill Foster, Member

1. **Does the development of broadband digital spread spectrum techniques for radio communications, which may be difficult to distinguish from "white noise" raise questions about SETI's abilities to detect similar signals from extraterrestrial sources?**

   Yes, broadband, spread spectrum, modulations are, in general, more difficult to detect than narrow-band modulation. We employ special algorithms to increase sensitivity to signals of this type, but they do increase the computational complexity of the search.