EXOPLANET DISCOVERIES: HAVE WE FOUND OTHER EARTHS?

JOINT HEARING

BEFORE THE

SUBCOMMITTEE ON SPACE &
SUBCOMMITTEE ON RESEARCH

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

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CONTENTS

Thursday, May 9, 2013

Page

Appendix II: Additional Material for the Record

EXOPLANET DISCOVERIES: HAVE WE FOUND OTHER EARTHS?

THURSDAY, MAY 9, 2013

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

The Subcommittees met, pursuant to call, at 10:05 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Steven Palazzo [Chairman of the Subcommittee on Space] presiding.

LAMAR S. SMITH, Texas
CHAIRMAN

EDDIE BERNICE JOHNSON, Texas
RANKING MEMBER

Congress of the United States
House of Representatives

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Subcommittee on Space
and
Subcommittee on Research

Exoplanet Discoveries: Have We Found Other Earths?

Thursday, May 9, 2013
10:00 a.m. to 12:00 p.m.
2318 Rayburn House Office Building

Witnesses

Dr. Laurance Doyle*, Principal Investigator, Center for the Study of Life in the Universe, SETI Institute, and member of the NASA Kepler Mission Science Team*

Dr. John Grunsfeld*, Associate Administrator, Science Mission Directorate, National Aeronautics and Space Administration*

Dr. James Ulvestad*, Division Director, Division of Astronomical Sciences, Directorate for Mathematical and Physical Sciences, National Science Foundation*

U.S. HOUSE OF REPRESENTATIVES
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SUBCOMMITTEE ON SPACE
AND
SUBCOMMITTEE ON RESEARCH

Exoplanet Discoveries: Have We Found Other Earths?

Thursday, May 9, 2013
10 a.m. – 12 p.m.
2318 Rayburn House Office Building

Purpose

The purpose of the hearing is to review the recent discovery of three super-Earth sized planets by the National Aeronautics and Space Administration's (NASA) Kepler space telescope. The hearing will also assess the state of exoplanet surveying, characterization, and research; NASA's Exoplanet Exploration Program; National Science Foundation's (NSF) Division of Astronomical Science; as well as coordination within the government and with external partners. NASA and NSF both contribute to the search for exoplanets. NASA provides space-based telescopes to identify potential planets, while NSF builds ground-based telescopes. Both agencies fund research that assists in categorizing and characterizing candidate planets.

Witnesses

- Dr. Laurance Doyle, Principal Investigator, Center for the Study of Life in the Universe, SETI Institute, and member of the NASA Kepler Mission Science Team;
- Dr. John Grunsfeld, Associate Administrator, Science Mission Directorate, NASA;
- Dr. James (Jim) Ulvestad, Division Director, Division of Astronomical Sciences, Directorate for Mathematical and Physical Sciences, NSF.

Overarching Questions

1. How is exoplanet research conducted and why is it important?
2. How do the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA) support exoplanet research?
3. What does future exoplanet research hope to discover?

Background

The first definitive exoplanet discovery occurred in 1992 by NSF-funded researchers.[1] On September 29, 2010, the Keck Observatory announced that it had identified the first Earth-sized

[1] http://tech.mit.edu/V114/N22/psr.22w.html

planet orbiting a star in a "habitable zone," an area where a planet's distance from its sun increases the possibility it could have surface temperatures that could support the existence of liquid water. [2] On April 18, 2013, NASA's Kepler mission released details of its discovery of two new planetary systems that include three super-Earth sized planets in the "habitable zone."[3] These discoveries heightened speculation about the possibilities of finding life on another planet than Earth.

NASA

On March 6, 2009, NASA launched the Kepler space telescope. Part of NASA's Explorer program, Kepler's purpose is to survey the Milky Way galaxy to find Earth-size planets and similar solar systems. From space, Kepler is able to identify smaller targets than ground-based telescopes. Originally slated as a three and a half year mission, operations could be extended until 2015; however, recent technical problems with the spacecraft may limit its continued operations.

Other NASA-sponsored telescopes involved in exoplanet research include the 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) to be launched in fall 2018, the newly announced Explorer mission Transiting Exoplanet Survey Satellite (TESS), and potentially the Wide Field Infrared Survey Telescope (WFIRST).

In FY 2013, NASA spent an estimated $41.6 million on exoplanet research. The FY 2014 budget request is $55.4 million.[4] This amount includes funding for extension of the Kepler mission and NASA's partnership with the Keck Observatory used for all NASA astrophysics science programs.

NSF

NSF-funded facilities play key roles in exoplanet research, including the Gemini Observatory in Hawaii, the Atacama Large Millimeter/Submillimeter Array (ALMA) in Chile, and the Arecibo Observatory in Puerto Rico. The NSF reports that requests for exoplanet research grants are the fastest growing component of proposals submitted to the Division of Astronomical Science.[5] In 2013, approximately 16 percent of projects reviewed by the Astronomy and Astrophysics Research Grants program were for exoplanet research.[6] There are currently more than 40 active awards covering exoplanets.

The estimated budget for FY 2013 for NSF's Division of Astronomical Sciences (AST) was $234.55 million and the FY 2014 budget request is $243.64 million. Much of AST's budget is for grants using NSF funded ground-based telescopes. In FY 2014, NSF has also requested an additional $28 million to begin construction on the Large Synoptic Survey Telescope (LSST), which will be used, in part, for exoplanet research.[7]

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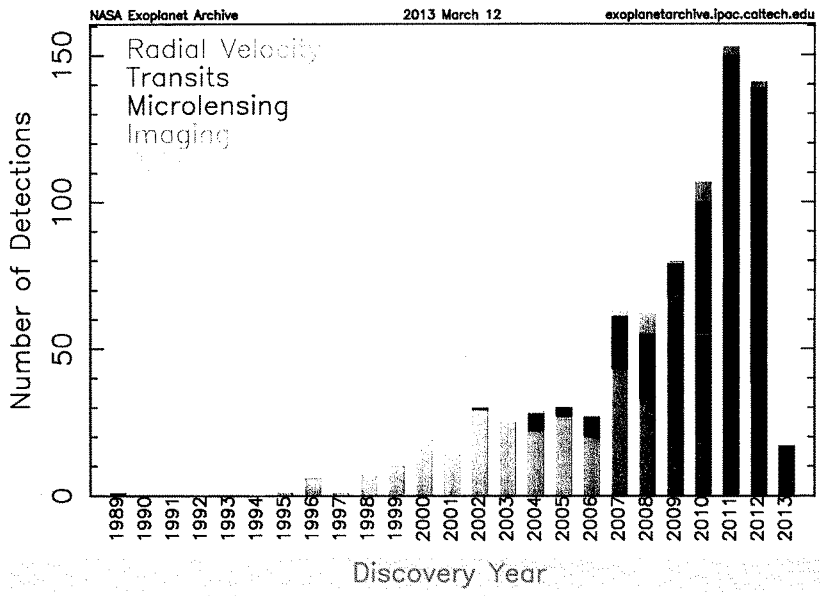
[2] http://keckobservatory.org/news/keck_observatory_discovers_the_first_goldilocks_exoplanet/
[3] http://www.nasa.gov/mission_pages/kepler/news/kepler-62-kepler-69.html
[4] http://www.nasa.gov/pdf/740512main_FY2014%20CJ%20for%20Online.pdf
[5] See Supra 4
[6] Ibid
[7] http://www.nsf.gov/pubs/2013/nsf13019/nsf13019.pdf

Key Detection Techniques[8]

In the past two decades, scientists have developed a variety of methods for detecting exoplanets. As the technology for observing planetary systems has improved, the number of new discoveries has increased and scientific interest in the field has grown. As of May 2013, there are roughly 900 confirmed exoplanets and more than 2,700 planet candidates.[9]

Exoplanet Discoveries[10]



Radial Velocity

The radial velocity technique uses infrared sensors and the Doppler Shift to detect a star's wobble as it is affected by the mass of an orbiting planet. This technique has identified 504 planets in 390 systems. *Example: NASA/Keck for discovery and Kepler for validation.*

Transit Technique

The transit technique uses optical measurements to detect a change in a star's brightness as a planet goes in front of or behind a star. This technique has identified 294 planets in 238 systems as well as

[8] NASA briefing to the House Science, Space, and Technology Committee, *NASA's Exoplanet Program: Leading the Quest to Discover and Characterize Planets Around Other Stars*, April 4, 2013.
[9] See Supra 4
[10] Ibid

more than 2,740 planet candidates. *Example: Kepler for discovery; Spitzer, Hubble &JWST for characterization.*

Direct Imaging

The direct imaging technique uses optical sensors to identify faint planets next to bright stars with coronographs and occulters. This technique has identified 30 planets in 27 systems. *Example: Hubble, JWST, and a potential New Worlds mission.*

Microlensing

Microlensing uses a star's gravitational field to bend light like a lens in order to find planets beyond the star. While this technique has only identified 19 planets in 16 systems so far, NASA's proposed WFIRST mission will use this promising technique to search for exoplanets. Where the Kepler mission is optimized for identifying planets close to stars, WFIRST will be optimized for planets farther away from stars.[11]

Habitability

Astronomers and astrophysicists use the term "habitability" as way to classify an exoplanet's potential for hosting organic life. This classification does not mean that the expoplanet may be habitable for human life, but that conditions exist where some kind of organic life could be found.

To calculate which exoplanets reside in a "habitable zone," scientists look at several factors[12]:

- Environment – the exoplanet's distance from its star helps determine the planet's stable temperature and orbital stability
- Planet size and mass – determining whether the planet has an active plate techtonic system (or rocky surface) and stable atmosphere provides scientists with evidence of an active carbon cycle
- Composition – evaluating the surface for the presence of water could be an indication of life

Exoplanets that appear to meet these criteria are referred to as "goldilocks" planets, because they are neither too hot nor too cold to sustain habitable conditions for life. Out of the 2700 planets identified by Kepler, 50 have been determined to be "goldilocks" planets.[13]

Future

The Astronomy and Astrophysics Advisory Committee (AAAC) advises NASA, NSF, and the Department of Energy (DOE) on common areas of astronomy and astrophysics. Established in the NSF Authorization Act of 2002, its purpose is to coordinate agency activities put forth in National Research Council (NRC) astronomy and astrophysics decadal surveys, assess programs, make recommendations, and to annually report on these findings to the participating agencies and Congressional committees of jurisdiction.

[11] http://wfirst.gsfc.nasa.gov/science/exoplanets/
[12] See Supra 7
[13] Ibid

The 2010 National Academies' decadal survey, *New Worlds, New Horizons in Astronomy and Astrophysics* referenced exoplanet research in the section titled "New Worlds: Seeking Nearby, Habitable Planets." The Academies listed the following questions regarding exoplanets:

- How do circumstellar disks evolve and form planetary systems?
- How diverse are planetary systems?
- Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet?[14]

In their March 8, 2013, report the AAAC released the following recommendations related to exoplanet research:

- NASA should continue funding the WFIRST mission, while concurrently funding completion of JWST.
- As the largest priority ground-based telescope in the 2010 NRC decadal survey "New Worlds, New Horizons in Astronomy and Astrophysics," NSF and DOE should continue funding development of the Large Synoptic Survey Telescope.[15]

The AAAC addressed exoplanet research specifically with their May 22, 2008 report of the Exoplanet Task Force titled "Worlds Beyond: A Strategy for the Detection and Characterization of Exoplanets." The Task Force developed a 15 year strategy for the detection and characterization of exoplanets and planetary systems, as requested by NASA and the NSF.[16]

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[14] http://www.nap.edu/catalog.php?record_id=12951

[15] http://www.nsf.gov/mps/ast/aaac/reports/annual/aaac_2013_130308finalreport.pdf

[16] For additional information, see http://www.nsf.gov/mps/ast/aaac/exoplanet_task_force/reports/exoptf_final_report.pdf

Chairman PALAZZO. This joint hearing of the Subcommittee on Space and the Subcommittee on Research will come to order.

Good morning, and welcome to today's joint hearing titled "Exoplanet Discoveries: Have We Found Other Earths?" In front of you are packets containing the written testimony, biographies and Truth in Testimony disclosures for today's witnesses.

Before we get started, since this is a joint hearing involving two Subcommittees, I want to explain how we will operate procedurally so all Members understand how the question-and-answer period will be handled. As always, we will alternate between the majority and minority members. We will recognize those Members present at the gavel in order of seniority on the full Committee and those coming in after the gavel will be recognized in order of arrival, and because of today's vote schedule, everybody, both minority and majority Members, have decided we are going to submit our opening statements for the record, which will allow us to proceed directly to our witnesses' testimony.

[The information follows:]

PREPARED STATEMENT OF SUBCOMMITTEE ON SPACE CHAIRMAN STEVEN PALAZZO

Good morning, and welcome to this hearing. I would like to thank our witnesses for being here today to testify about exoplanet research and to share information with us about the recent discoveries made by NASA's Kepler mission.

I would also like to commend NASA and NSF for working to meet our Committee's testimony deadlines. I understand that their testimony was late because the Office of Management and Budget failed to manage their time and resources wisely. In this case, I do not want to hold NASA or NSF responsible for problems in other areas of the Administration.

Today's hearing topic is an exciting one. As of May 2013, scientists had identified roughly 900 confirmed "exoplanets"—planets beyond our solar system—and more than 2,700 planet candidates. Last month, NASA's Kepler mission announced that it had found three super-Earth sized planets in the "habitable zone" of two stars in our galaxy. The "habitable zone" refers the region around stars where planets could support liquid water. This discovery has broad implications not only for the scientific community, but for all mankind. This research will provide us with a better understanding of the universe and inspire the next generation of scientists and engineers.

NASA's Fiscal Year (FY) 2013 budget allocates roughly $41million for exoplanet research, while the FY 2014 budget request is $55 million. This amount includes funding for the extension of the Kepler mission and NASA's partnership with the Keck Observatory used for all NASA astrophysics science programs.

According to Dr. Laurance Doyle, one of our witnesses today, exoplanet research was not as popular when he entered the field 30 years ago as it is today. Now there are at least several thousand astronomers and astrophysicists around the world applying the transit method, like the one used by the Kepler mission, to detect and study extra-solar planets. In addition to the Kepler mission, the agency is planning to use future missions to further exoplanet research, including the James Webb Space Telescope, the Wide-Field Infrared Survey Telescope, and the newly announced Transiting Exoplanet Survey Satellite (TESS), which is expected to study the nearest bright stars and potentially discover thousands of new planets.

I look forward to hearing about NASA and NSF's plan for continuing exoplanet research using these unique capabilities. Additional discoveries will no doubt accompany the development of these capabilities, which will in turn inspire new astronomers and astrophysicists.

I am also interested in understanding how the government can increase cooperation to further leverage our investments. The Astronomy and Astrophysics Advisory Committee's (AAAC) Exoplanet Task Force and the National Academies have issued recommendations and roadmaps to guide future investigations. As the Academies notes in their recent decadal survey, "[t]he search for exoplanets is one of the most exciting subjects in all of astronomy." The report went on to recommend "a program to explore the diversity and properties of planetary systems around other stars, and to prepare for the long-term goal of discovering and investigating nearby, habitable planets."

The AAAC's Exoplanet Task Force issued a report in 2008 that posed the following questions regarding exoplanets: Do Earth-like planets exist; are they common; and do they show signs of habitability or biosignatures? These are complex questions that the National Academies' decadal survey argues will ultimately require a dedicated space mission to answer. However, that same decadal survey went on to state that "it is too early to determine what the design of that space mission should be, or even which planet-detection techniques should be employed. It is not even clear whether searches are best carried out at infrared, optical, or even ultraviolet wavelengths."

As we strive to do more with less, I hope we will get a better understanding of how exoplanet research should adapt to the fiscal realities we face today. Is the current portfolio of missions and research still the ideal path under constrained budgets? How can we build upon recent inspirational discoveries in the most efficient manner? These are key questions we must answer as we work to draft a NASA Authorization Bill and a Reauthorization of COMPETES Act.

PREPARED STATEMENT OF SUBCOMMITTEE ON SPACE RANKING MINORITY MEMBER DONNA EDWARDS

Good afternoon and welcome to our distinguished panel of witnesses.

The news coming out of NASA a few weeks ago was both surprising yet not unexpected. NASA's Kepler space telescope had found Earth-sized and super-Earth sized planets. That was not unexpected as Kepler is doing a fantastic job at discerning these faint objects.

What was tantalizing is that this particular detection included three super-Earth-size planets in the "habitable zone," the range of distance from a star where the surface temperature of an orbiting planet might be suitable for liquid water to exist.

I say tantalizing because this finding means we are making progress in answering the fundamental questions of where do we come from and whether we are alone in the Universe. NASA and the National Science Foundation have exciting exoplanet research both underway and planned that will help us gain further insight into those questions.

Unfortunately, as we will hear this morning, addressing those questions will take time and resources; two things that are hard to come by in this difficult budgetary environment.

In particular, NASA is somewhat hamstrung in starting a new large mission in astrophysics until it is closer to launching the James Webb Space Telescope, currently slated for 2018. And NSF's ability to support a growing number of grant requests focused on exoplanet research is threatened by relatively flat funding and the need to maintain currently operating facilities.

I hope that today's hearing will shed light on the exciting potential of NASA and NSF exoplanet activities as well as the challenges these agencies face in getting there.

Prepared Statement of Subcommittee on Research and Technology Chairman Larry Bucshon

Since humanity first began looking to the heavens, we have been fascinated by the possibility that we may not be alone in the universe. We dreamt of worlds far away, but not unlike our own, long before the first exoplanet was discovered by researchers funded by the National Science Foundation in 1992. The National Science Foundation's Division of Astronomical Sciences has continued to play a crucial role in furthering these discoveries, providing funds to help build and operate ground-based telescopes used for exoplanet discovery and observation.

As the number of confirmed and cataloged heavenly bodies has swelled in the past twenty one years, we have sought to learn more about the conditions on these planets: the temperatures, the atmospheres, their core composition, how they orbit their respective stars, and ultimately, whether any are capable of sustaining life. We will hear from our witnesses today about "habitable zones," the distance from a star that creates conditions hospitable to life. We believe that 50 out of the 2700 exoplanet candidates identified by NASA's Kepler mission exist in the "goldilocks" zone, neither too hot nor too cold, and potentially just the right temperature to allow life to flourish. Just last month, the Kepler mission released the details of three "super-Earth" sized planets in the habitable zone. I look forward to hearing from our witnesses regarding their suggestions for the next steps in studying these super-Earth sized planets in particular, as well as surveying for additional exoplanets.

I would like to highlight the important contributions to life sciences research in space of two individuals affiliated with Purdue University back in my home state of Indiana. Dr. France Cordova, President Emerita of Purdue University is the Chairman of the Board of the Center for the Advancement of Science in Space, which manages the National Laboratory aboard the International Space Station. Dr. Marshall Porterfield, currently on leave from Purdue, is the Director of NASA's Space Life and Physical Sciences Research and Applications Division. At Purdue, he is a professor of agriculture and biological engineering, as well as co-director of the Physiological Sensing Facility, which fosters interdisciplinary engagement between bioscientists and engineers to drive sensor development and application. We are all very grateful for their service to our nation, and I am very pleased to know that their work will benefit not only the astronauts and scientists of today, but the students of Purdue University who will be studying these complex problems in the years to come.

Prepared Statement of Subcommittee on Research and Technology Ranking Minority Member Daniel Lipinski

Thank you Chairmen Palazzo and Bucshon for holding this hearing and thank you to the witnesses for being here. I will keep this brief.

The search for habitable planets outside of our own solar system was identified as a scientific priority in the 2010 National Academies Decadal Survey of Astronomy and Astrophysics. And no wonder. This is exactly the type of scientific pursuit that expands our understanding of the world, or worlds, around us and grips the imagination of scientists and the public at large, even though we have no idea what we will find.

Exoplanet research is also a good example of an area of science that receives support from more than one federal agency. In this case, NASA and NSF have overlapping science goals, but very different tools with which to pursue those goals. As a result, the data and findings generated by NASA's space-based instruments may map directly onto data and findings generated by NSF's ground-based instruments, permitting the kind of replication that drives scientific discovery forward. I could also note that the recent paper describing the new exoplanet that was found in a so-called habitable zone was co-authored by a researcher being funded by an NSF CAREER award, which funds early career researchers. I look forward to hearing more about the scientific opportunities made possible by current and future instruments at both agencies.

The collaboration between NSF and NASA on astronomy and astrophysics research appears overall to be strong and productive. The Astronomy and Astrophysics Advisory Committee, which was established by Congress in the 2002 NSF Reauthorization Act to address structural problems in interagency collaboration that were a real concern 10 years ago, have been very positive in their assessments in more recent years.

At the same time, both NASA and NSF have been under budgetary constraints that have hampered progress in astronomy and many other fields of science, even as the quantity and quality of proposals continues to increase. I'd like to hear from the agency representatives how you are dealing with these funding challenges for exoplanet research specifically and astronomy more generally, and any other challenges you may be facing.

PREPARED STATEMENT OF COMMITTEE ON SCIENCE, SPACE AND TECHNOLOGY CHAIRMAN LAMAR S. SMITH

Thank you Chairman Palazzo and Chairman Bucshon for holding this hearing. I also want to thank the witnesses for being here to share their expertise on this topic.

Space exploration is an investment in our nation's future—often the distant future. It encourages innovation and improves Americans' quality of life. I don't know if space is the final frontier, but I believe it is the next frontier.

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

The discovery of Earth-like planets will open up new opportunities for American astronomers and explorers. Some experts predict that many more planets will be detected soon. And some of these planets could even contain the first evidence of organic life outside of Earth.

Imagine how the discovery of life outside our solar system would alter our priorities for space exploration and how we view our place in the universe.

Today we will hear where we are in our search. And what comes next in our study of these newly discovered planets. The U.S. already has undertaken a number of initiatives.

Cooperation between NASA's space-based telescopes, like the Kepler mission, and ground-based telescopes funded in part by the National Science Foundation (NSF), has enabled astronomers to expand their star gazing capabilities. Also, next year construction will begin on the new NSF funded Large Synoptic Survey Telescope in Chile.

In addition to its many other capabilities, this telescope will essentially take a 10-year time lapse photo of the universe. The data collected from the telescope will help astronomers confirm the existence and types of exoplanets in our solar system.

The James Webb Space Telescope will use both transit spectroscopy and direct imaging to determine the make-up of exoplanet systems in our galaxy. This is an exciting time in the fields of astronomy and astrophysics. I look forward to hearing our witnesses' perspectives on these issues.

Thank you, Mr. Chairman, and I yield back the balance of my time.

Chairman PALAZZO. Now I will introduce our panel of witnesses. Our first witness is Dr. Laurance Doyle, the Principal Investigator for the Center for the Study of Life in the Universe at the SETI Institute. Our second witness is Dr. John Grunsfeld, the Associate Administrator of the Science Mission Directorate at the National Aeronautics and Space Administration. And our final witness is Dr. James Ulvestad, Director of the Division of Astronomical Sciences at the National Science Foundation. Previously, he was the Assistant Director of the National Radio Astronomy Observatory. He served in various capacities at the NASA Jet Propulsion Laboratory, where he played an important role in several interagency and international programs.

As our witnesses should know, spoken testimony is limited to five minutes each after which Members of the Committee have five minutes each to ask questions. Your written testimony will be included in the record of the hearing.

I now recognize our first witness, Dr. Doyle, for five minutes for his testimony.

TESTIMONY OF DR. LAURANCE DOYLE, PRINCIPAL INVESTIGATOR, CENTER FOR THE STUDY OF LIFE IN THE UNIVERSE, SETI INSTITUTE

Dr. DOYLE. Thank you for inviting me. It is an honor to be here.

My work in extrasolar planet research stretches back about 30 years, which is a decade before the first extrasolar planets were actually discovered. At that time there were only two other people in the world working on the transit method, John Schneider and William Borucki, who is the PI of Kepler. The transit method involves the detection of a planet as it orbits in front of its star. In other words, one could say that one is detecting the shadow of the planet. Today there are thousands of astrophysicists and their students working using the transit method to study and detect extrasolar planets.

In the early years of this research, I was able to identify three methods for detecting extrasolar planets. In the 1990s I directed an international network of telescopes to search for circumbinary planets. As a participating scientist with Kepler, I have been able to collaborate with the eclipsing binary working group in the discovery of several thousands of new eclipsing binaries. These are stars that orbit in front of each other, and if they are in the background of an extrasolar planet, they can look like the transit of a planet, so you have to catalog all the eclipsing binaries.

My main work, though, as a participating scientist with Kepler has been the detection of circumbinary planets, that is, planets that orbit around two stars at the same time. This was—the first transiting circumbinary planet was discovered in 2011, and it was called Kepler-16b. We began calling this planet Tatooine, because the Star Wars hero Luke Skywalker was watching a double sunset. And what we didn't know is someone called George Lucas and asked him if we could nickname it Tatooine and he sent the Director of Industrial Light and Magic to the NASA press conference. So basically worldwide press picked up this as "Tatooine discovered," but it was a great example of science fiction turning into science fact. And I like to think it had inspired many students worldwide to study math and science so they could turn science fiction into science themselves someday.

In the context of the search for life in the universe, the Kepler mission has already made a huge contribution. At the SETI Institute, we have scientists working on all aspects of detection of life in the universe, including robotic landing missions and radio telescope searches. About 50 SETI Institute scientists are currently working on the Kepler mission. For about 50 years, SETI astronomers could only target stars. Now that Kepler has discovered the frequency of planets, we now can actually target planets that we know to be in the habitable zone of their stars. This is a huge step as far as the search for extraterrestrial intelligence.

The next step in detecting life in the universe will be most likely to find biomarkers in the atmospheres of extrasolar planets. An example of this is oxygen, which is highly indicative of photosynthetic systems like forests, seaweed, microflora and so on. Taking a remote spectra of the Earth, the detection of oxygen would be indicative of plant life, possibly animal life, and maybe even intelligent life. So, it could be that the first detection of extraterrestrial life will be forests.

Finally, to answer the question that is the title of this session, "Have we found other Earths?" we know that the best candidate to date is Kepler-62f, but it is also 1.4 times the Earth's radius. It may be slightly too big to recycle its atmosphere with plate tectonics, but we don't know for sure. A lot of modeling still has to take place. So I would say the safe answer to the question is "almost."

Within the next few years, Kepler will likely be able to detect exactly Earth-size planets. To put this in perspective, 2,400 years ago, the ancient Greek philosopher, Metrodorus of Chios wrote this: "To consider the Earth as the only populated world in infinite space is as absurd as to assert that in an entire field sown with millet, only one grain will grow." Within the next few years we will have the privilege of finding the actual answer to this age-old question: "In the universe, is there another place like home?" I think with the Kepler mission, we are just on the verge of answering "yes."

[The prepared statement of Dr. Doyle follows:]

Carl Sagan Center for the Study of Life in the Universe

SETI INSTITUTE

May 9, 2013

Testimony to the Subcommittees on Space and Research of the Committee on Science, Space, and Technology, of the U.S. House of Representatives, Congress of the United States of America

Exoplanet Discoveries: Have We Found Other Earths?

Thursday, May 9th, 10:00 am – 12:00 pm, Room 2318 of Rayburn House Office Building

Dr. Laurance R. Doyle – SETI Institute

This testimony addresses the following topics: (1) presenter's work in exoplanet research; (2) resources, technologies, and methods used to do this work, including the Kepler telescope; and (3) future programs focused on exoplanet research.

The author's work in exoplanet research extends back 30 years, a decade before extrasolar planets were discovered. At that time there were apparently only three people in the world working on the transit method for extrasolar planet detection—the author, Jean Schneider in France, and William Borucki, the current Principal Investigator of the Kepler Mission. The transit method involves the detection of a planet as it moves across the disc of a star. In other words, one could say that it is the shadow of the planet that is detected. Today there are at least several thousand astronomers, astrophysicists, and their students throughout the world applying the transit method to detect and study extrasolar planets.

In the early years of this research, the author identified three new methods for the detection of extrasolar planets and, in the 1990s, did the first search for super-Earth-sized planets in the habitable zone of another star, directing a network of telescopes spaced around the Earth at different longitudes (Doyle et al. 2000, *The Astrophysical Journal* **535**, 338-349). As a Participating Scientist on the Kepler Science Team, the author was asked by the Principal Investigator to organize an eclipsing binary star working group. Eclipsing binary star systems are double stars that orbit in front of each other across our line of sight, so that they eclipse each other every orbital period. Background eclipsing binaries can look like foreground planetary transits, so it is important to know the eclipsing binaries in the Kepler telescope field of view so they will not be mistaken for new planets. Every one of the planets discovered by the Kepler mission had to pass such a test before it could be confirmed as a real planet. The author also participated in the compilation of two Kepler eclipsing binary catalogues that included the discovery of between two and three thousand new eclipsing double star systems.

Another task the author has been performing for the Kepler mission is assisting in the definition of habitable zones around stars with planets in or near the circumstellar habitable zone—planets Kepler-62e and -62f being a recent example (Borucki et al. 2013, *Science* **387**, 587-590). The habitable zone around a star is the region where an Earth-sized planet may be able to maintain liquid water on its surface for an extended period of time. The assumption is, of course, that water is required for habitability, which is certainly the case for biology as we know it on Earth. At some point too close to a star, any oceans on a planet will evaporate. At another point too far from the star, the atmosphere will completely condense out as snow, and the planet will completely freeze over. In our own solar system, Venus and Mars, respectively, illustrate the basic concepts. The author has worked in this field since 1994, when he organized a conference on habitable zones (*Circumstellar Habitable Zones*, L.R. Doyle, ed., Travis House Publications, Menlo Park, CA), which was one of the precursors of the concept embodied in the current NASA Astrobiology Institute program which brings together multidisciplinary scientists such as biologists, astrophysicists, and planetary geologists to answer questions about life in the universe.

The author's main work with the Kepler Spacecraft has, however, concerned the detection of "circumbinary planets"—that is, planets that orbit around two stars at once; the planet circles around both stars as they orbit around each other. Before Kepler there were a handful of circumbinary planet candidates, but the planet formation community was split as to whether such double-star planets could really exist. With the discovery of the first transiting circumbinary planet, Kepler-16b, we were able to prove that such double-star planets do exist (Doyle et al. 2011, Science **333**, 1602-1606). Planetary transits across two moving stars are more complicated than transits across single stars, but since the discovery of Kepler-16b we have found about half a dozen additional such systems, several within the habitable zone of their (combined) stars. However, they are all large planets—closer in mass to, for example, Neptune. The scientific importance of these discoveries is that such double-star planetary systems are a fundamentally new kind of solar system. In science, the discovery of a new *kind* of phenomenon allows previous discoveries to be seen in context. The discovery of a new kind of biology on Mars would be an example; the origin of biology on Earth could be seen in the context of its origin elsewhere. In the case of Kepler-16b—and subsequent circumbinary planets—here was a fundamentally different kind of solar system where the planets form around and orbit two stars. Half the stars in our galaxy are double stars, so these discoveries bode well for life in the universe. Some of the excitement upon the announcement of the discovery of Kepler-16b also came from nicknaming this planet "Tatooine," after the home planet of *Star Wars* hero Luke Skywalker. Luke, in the film, spent some time watching a double sunset, a view that only became a reality with the discovery of Kepler-16b. George Lucas actually sent the Director of Industrial Light and Magic, John Knoll, to the Kepler-16 NASA press conference and the worldwide press picked up the discovery as a great example of science fiction becoming science fact. This discovery also reached a lot of students worldwide—from the correspondence received by the author—hopefully inspiring them, too, to make such real discoveries for themselves.

As mentioned, the transit method for detecting extrasolar planets detects the planet as it moves across—that is, "transits"—its parent star. While the Hubble Space telescope produces pictures, the Kepler Spacecraft produces what are called "light curves." A light curve is a measurement of the brightness of a star plotted over a given time span. Some stars pulsate, some eclipse each other, and some are very steady in their brightness such as our Sun. A light-curve plot of brightness with time reveals how each of these types of stars behaves in varying its light output. And, if the light curve is accurate enough, it can reveal if there are any planets orbiting across our line of sight in front of the star, momentarily blocking out a little bit of the starlight. Not every star will have planets that happen to orbit edge-on, however, so one has to look at many stars to catch the small percentage with planets whose orbits are edge-on. Thus the Kepler telescope is an extremely wide-angle telescope that can view millions of stars continuously, with about 170,000 of the brightest stars being examined for planetary transits. The Kepler Spacecraft has been able to measure the brightness of stars about 100 times better than has ever before been achieved (on the ground or in space). As a consequence, it has revolutionized several astronomical fields such as eclipsing binary star systems, asteroseismology (the study of "starquakes" that tell about the interior of stars) as well as, of course, the field of extrasolar planets.

In the context of the search for life in the universe, the Kepler mission has made major contributions. This can be seen using the Drake Equation, which is a way of organizing the search for extraterrestrial intelligence, and the umbrella under which research is organized at the SETI (search for extraterrestrial intelligence) Institute, where the author works. (Incidentally, fifteen scientists from the SETI Institute currently work on the Kepler mission.) The Drake Equation is the product of the following terms: N = R* x Fp x Ne x Fl x Fi x Fc x L. Each of these terms are actually fields of research in themselves. For example *R** refers to stars (created per year) that have stable habitable zones around them, that is stars that do not vary in brightness by too much. Consequently such "good" stars do not either burn and freeze their planets. *Fp* is the fraction of such "good" star that actually have planets. *Ne* is the number of planets that happen to orbit within the habitable zone of their stars. *Fl* is the fraction of potentially habitable planets that are, in fact, inhabited (by any biological forms). And the factors *Fi, Fc,* and *L* refer to the fraction of intelligent species of all species on an inhabited planet, the fraction of those intelligent species that develop technology capable of interstellar communication, and finally the lifetime of such advanced technological civilizations, respectively. Radio SETI—listening for signs of technology in space—is about 50 years old, and the term *R** has been known fairly well for this half century. The number of Sun like stars in our galaxy is about 30 billion with some cooler stars than the Sun also apparently having good habitable zones. The breakthrough that has been made with the work of the Kepler spacecraft over the past four years, is that a robust determination of *Fp*, the frequency of stars with planets, has now been definitively determined. Kepler has established the frequency of planets around the stars in only four years since its launch.

Finally, and most exciting to the SETI community, Kepler is discovering the value of *Ne*, the number of truly *Earthlike* planets within the habitable zones of their parent stars. To put Kepler's discoveries in this context, of the seven factors in Drake's Equation, one term, *R**, has been known for more than half a century, and in the past four years, the Kepler mission has determined the next term, *Fp*, and will soon add a determination of the third term, *Ne*, within the next few years. In the context of studies of life in the universe, this is a huge accomplishment, and radio astronomers at SETI

Institute are now targeting these Kepler planets known to orbit within the habitable zone. of their stars.

In the context of the Drake Equation, the next step in the discovery of life in the universe, illustrated by the term *Fl*, will be a next generation of telescopes that can discover biomarkers—evidence of life—in the atmospheres of Earthlike planets. An example of such a biomarker can be drawn from our own planet. The element oxygen is very reactive and so should, therefore, react with rocks or the ocean and consequently be removed rather rapidly as a constituent of our atmosphere. Yet oxygen is abundant in the Earth's atmosphere. This means that something must be producing it constantly in prodigious amounts. The large amount of free oxygen in the atmosphere of Earth, therefore, shows that we have huge photosynthetic systems operating here, including forests, seaweeds, and microflora. Taking remote spectra of the Earth, the detection of oxygen would be a major clue that the Earth does, indeed, harbor plant life and therefore possibly animal life, and perhaps even intelligent life. Thus with new missions to detect such biomarkers, it could be that forests may be the first extraterrestrial life that will be detected.

Finally, to answer the question that is the title of this session, *Exoplanet Discoveries: Have We Found Other Earths?* which is referring to the recent discovery of two planets within the habitable zone of the star Kepler-62. These planets—Kepler-62e, which is 1.6 times the radius of the Earth, and Kepler-62f, which is 1.4 times the radius of the Earth—are located within the habitable zones of their parent stars. Kepler-62f is actually more in the center of its habitable zone than the Earth is in our own Sun's habitable zone (we are closer to our inner boundary). So it is not the location of the planets that causes one to hesitate ... just a bit; it is their sizes. On Earth, the moving tectonic plates that make up continents are constantly being melted down as they dive under other continental plates. (The Pacific Plate and the North American Plate are well-known examples, meeting on the San Andreas Fault line.) This process of recycling continental rocks releases their gases back into the air. Plate tectonic activity stopped on Mars billions of years ago, so the atmosphere that did not leak into space was caught up in the rocks of Mars. Mars was too small, however to keep plate tectonics going. Some recent models have also found that if a planet is too large—near 1.4 Earth radii, for example,—a thick geological crust may possibly form that might also have the effect of stopping the plate tectonic recycling of the planet's atmosphere as well. Could this have happened to Kepler-62f? That will have to be further investigated. In the meanwhile, then, we will have to be just a bit cautious about claiming the habitability of Kepler-62f.

Fortunately, the discovery of even smaller planets than Kepler-62f within the habitable zone of their parent stars is still to come for the Kepler mission, and within the next few years Kepler will very likely find a true Earth-sized planet within its star's habitable zone. Writing 24 centuries ago in ancient Greece, Metrodorus of Chios said, "To consider the Earth as the only populated world in infinite space is as absurd as to assert that in an entire field sown with millet, only one grain will grow." Within the next few years we will have the privilege, through the Kepler Mission, to have the answer to this age-old question: "In the universe, is there another place like home?" I think we are on the verge of answering, "Yes!"

Short Narrative Biography (2013) - Dr. Laurance R. Doyle

Dr. Doyle was raised along the California coast in the small town of Cambria. He attended San Diego State University and after receiving his Bachelor and Master of Science degrees in astronomy, he worked as an engineer with the Voyager spacecrafts in the Space Image Processing Group at the NASA Jet Propulsion Laboratory. He thereafter received his PhD from the University of Heidelberg in Germany in 1987 on radiative transfer modeling of Saturn's rings using Voyager spacecraft imaging data. Since 1987 he has been a Principal Investigator with the SETI Institute in Mountain View, California where his main projects have been the photometric detection of extrasolar planets, the application of information theory to animal communications, and the application of quantum physics to astronomical scales. He was a visiting Lecturer at the University of California, Santa Cruz for seven years teaching classes on Life in the Universe, and Light & Optics. He has taught quantum physics, thermodynamics, introductory astronomy, history of science and Native American history at Principia College in Illinois was the visiting Annenberg Scholar for academic year 2011-2012. He has lectured for the Christian Science Board of Lectureship and has been a contributing editor for the *Christian Science Sentinel*, the *Christian Science Journal*, and the *Christian Science Monitor*. He has been a Member of the NASA Kepler Science Team and—as a Participating Scientist—had responsibility for detection of extrasolar planets around double star systems, announcing the detection of the first transiting circumbinary planet in 2011. He has about one hundred refereed papers in the scientific literature.

Chairman PALAZZO. I now recognize our next witness, Dr. Grunsfeld.

TESTIMONY OF DR. JOHN M. GRUNSFELD, ASSOCIATE ADMINISTRATOR, SCIENCE MISSION DIRECTORATE, NASA

Dr. GRUNSFELD. Mr. Chairman, Members of the Committee, thank you very much for the opportunity to appear before you today to discuss what I consider an incredibly exciting subject: extrasolar planets. As you have just heard, or exoplanets, which are defined as planets orbiting stars other than our own sun.

As a young boy growing up in Chicago, I quite often laid on the grass at night looking up at the stars wondering is anybody out there, and even explicitly, are there planets around any of these stars. This wonder about the universe and the question of whether there are exoplanets helped to drive me into a career in science and engineering, ultimately to become an astronaut and now the head of Science Mission Directorat at NASA.

NASA plays a key leadership role in the quest to discover and characterize distant exoplanets and search for life in the universe. We work with a variety of space-based and ground-based telescopes and in concert with the National Science Foundation and our international partners in observatories around the world.

Since the first exoplanet discoveries in the 1990s, over 900 exoplanets have been discovered. There is an app on your smartphone you can check daily if you are really curious, and in just the last four years the Kepler mission has contributed over 122 confirmed exoplanets and has over 2,700 candidates most of which will probably turn out to be real exoplanets.

Thanks to the Kepler mission, the statistics suggest that when you look up at the night sky, outside of the District, of course, because it is hard to see very many stars, virtually all of those stars have planets. At least one planet and perhaps a whole solar system around them. Even more exciting is the more commons star in our galaxy, an M-class star. About 15 percent, or one in six of those stars, has a rocky planet in the habitable zone, and that is what Kepler has told us, if the statistics hold out more generally.

The Kepler team recently announced the discovery of rocky planets a little bigger than the Earth around their host stars and one of which, Kepler-69c, around a star very much like our own sun. The nearest habitable exoplanet, habitable meaning liquid water could exist on its surface, may be as close as 15 light-years away.

When the Hubble Space Telescope was launched, no exoplanets had been found and we had nine planets in our own solar system, now eight. Since then, the Hubble has not only directly imaged solar systems, one with three planets, but it has also measured the components of the atmosphere around one of those planets. Along with Kepler and Hubble, the Spitzer Space Telescope, the NASA Keck ground-based telescope in Hawaii and many other ground-based telescopes are contributing to the rapid pace of discovery in this exciting field.

In 2018, we will launch the James Webb Space Telescope, and that will give us a big leap in capability and our ability to study exoplanets. When we started designing the James Webb Space Telescope, again, we had not yet discovered any exoplanets. But its infrared capability, the fact that it has a coronagraph and its ability to take the spectrum of the light from these exoplanets will really tell us a lot about the atmospheres and the components of those systems.

But even before James Webb Space Telescope, we are going to launch the Transiting Exoplanet Survey Satellite just selected as part of our Explorer program and it is going to do an all-sky survey of the nearest and brightest stars, our neighbors, to see if there transiting exoplanets around those stars. With the TESS information, we will be able to target the James Webb Space Telescope, also the Atacama Large Millimeter Array sponsored by the National Science Foundation to really learn about these closest neighbors. All these telescopes will work together to answer the basic questions about these distant solar systems: determine the size of the planets, their mass, their characteristics, their atmosphere, their composition. Very exciting work ahead.

Looking to the future, NASA funds technology development for exoplanet research and is studying the use of an existing telescope asset you may have heard about that we got from the National Reconnaissance Organization that will have a coronagraph that will be able to study the atmosphere of these distant plants in much more detail by directing imaging. We are also studying other techniques that will be infused into future telescopes that will be able to characterize an Earth-sized planet around a nearby star and search for evidence of life beyond our solar system.

NASA is aware that exoplanets are of great interest to the public, the science community, and they bring together many scientific disciplines. That is one of the reasons why all of our data from Hubble, Spitzer and Kepler is all made available to the public, and this has resulted in an explosion of discoveries well beyond the NASA-funded research, including a number of discoveries by citizen scientists.

In conclusion, NASA has a comprehensive program to detect and characterize exoplanets. And with the progress we have already made, I am confident that it is not a question of whether or not we will find an Earth-like exoplanet but when. With our program, the active participation of a rapidly growing scientific community, and our partners, we will continue to make major strides forward in our understanding of the science of exoplanets, and programs like Kepler capture the imagination of everyday people. I think that is why you are all here, that you are also interested including our students, who will be the scientists and engineers of tomorrow. NASA has exciting missions like the Hubble, the James Webb Space Telescope, TESS and Kepler to reach even farther back in time, to unravel the mysteries of the universe, and to start characterizing and analyzing the atmospheres of exoplanets. The future of exoplanet research is bright, and NASA will continue to play a leadership role in that future.

I look forward to your questions, and I have one very short comment, which is, at the end of almost every public presentation I make, I have a quotation—it is a quotation from Tennyson that I have editorially modified, and it says "For I dipped into the future as far as human eyes could see, saw the vision of the new worlds and all the wonders that would be.” Thank you very much.

[The prepared statement of Dr. Grunsfeld follows:]

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May 9, 2013

Statement of
Dr. John M. Grunsfeld
Associate Administrator
Science Mission Directorate
National Aeronautics and Space Administration

before the

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

Mr. Chairman and Members of the Committee, thank you for the opportunity to appear today to discuss the topic of extrasolar planets, or simply exoplanets, which are defined as planets that orbit a star other than our own Sun.

NASA thrives on the synergy created by a critical mass of brilliant scientific and engineering talent, supported by a broad range of expert professionals. We work, as an Agency, to send humans to an asteroid and on to orbit Mars. We work, as an Agency, to understand the universe from the beginning of time to the future of Earth's climate. NASA's budget request for 2014 fully funds the James Webb Space Telescope for launch in 2018, and supports a Mars lander for launch in 2020. The request supports development of critical human exploration capabilities, and space technology to enable our future in space. With the 2014 request NASA is planning a first-ever mission to identify, capture, and redirect an asteroid into orbit around the Moon. This mission represents an unprecedented technological challenge -- raising the bar for human exploration and discovery, while helping protect our home planet and bringing us closer to a human mission to Mars in the 2030s. The President's budget request for NASA advances a strategic plan for the future that builds on U.S. preeminence in science and technology, improves life on Earth, and protects our home planet.

Within the broader agency mission, NASA's Exoplanet Exploration Program focuses on answers to fundamental questions that are likely as old as humankind itself: 1) Are there other planets in the universe? 2) Are there other planets just like Earth out there? and 3) Are we alone? While these questions have been the subject of speculation since humankind first gazed to the heavens and wondered what was out there, the scientific study of these intriguing objects is relatively new; the first confirmed discoveries of exoplanets did not occur until the 1990s. In the intervening years, scientists have discovered over 850 exoplanets, with new ones being discovered almost daily. In just the last 4 years, NASA's Kepler mission has contributed 122 confirmed exoplanets and more than 2,700 exoplanet candidates, and scientists expect that a large fraction of those candidates will ultimately be confirmed as exoplanets. Confirmed exoplanets are planets that astronomers have proven to a high degree of confidence, using multiple observations and, sometimes, two or more different instruments. This is an exciting time for exoplanet exploration, and the next few years will permit major leaps forward in our understanding of how many there are, how they formed, and whether they might have conditions that are hospitable to life as we know it – a condition that is called habitability.

Thanks to the Kepler mission, we now know that when you go outside and look up at the night sky, virtually every star you see has at least one planet around it. Based on the latest Kepler results, scientists estimate that at least 17 percent of all the stars out there have rocky planets orbiting them. Of even greater interest, the results suggest that 15 percent of M stars -- the smallest, coolest class of stars, but also by far the most common type of star in the galaxy -- have rocky planets in the habitable zone. This number tells us that the nearest potentially habitable planet could be only 15 light-years away. Moreover, if that trend holds for other classes of stars, it would mean that there are approximately 50 billion potentially habitable rocky planets spread throughout our own galaxy.

NASA's Exoplanet Exploration Program is leading the quest to discover and characterize exoplanets and search for life in the universe. There are several key exoplanet detection techniques in use today, with the most prolific being the radial velocity and the transit techniques. The radial velocity technique uses Doppler shifts in the light of a star to detect the tiny wobble caused by a planet orbiting around it. This technique is employed by astronomers to detect exoplanets using large ground-based telescopes around the world including by NASA-funded scientists at the Keck telescopes in Hawaii. The transit technique measures the tiny decrease in the brightness of a star that occurs when an orbiting planet passes in front of it. The transit technique is the method used by NASA's Kepler mission to detect exoplanets. NASA's Spitzer and Hubble Space Telescopes (HST) have also used the transit technique for characterization of exoplanet atmospheres, as will NASA's James Webb Space Telescope (JWST) when it launches in 2018. Other techniques for exoplanet detection and characterization include direct imaging and gravitational microlensing. Direct imaging uses a coronagraph or occulting mask to block light from the central star so the much fainter planet nearby can be discerned. The Keck telescopes, HST, and, when launched, JWST are all capable of direct imaging. Microlensing uses Einstein's gravitational bending of light to find planets orbiting distant stars or isolated planets free floating in interstellar space. NASA is studying a wide-field infrared survey telescope, the highest priority large-scale space-based activity of the National Academy of Sciences' most recent decadal survey in astronomy and astrophysics, which will use this technique to detect exoplanets, and may employ other technology to characterize exoplanets.

Current State of Exoplanet Exploration
NASA's Kepler mission is revolutionizing the search for extrasolar planets. Launched in March 2009, NASA's Kepler Space Telescope searches for exoplanet candidates by continuously measuring the brightness of more than 150,000 stars. When a planet candidate passes, or transits, in front of the star from the spacecraft's vantage point, light from the star is blocked. Different sized planets block different amounts of starlight. The amount of starlight blocked by a planet reveals its size relative to its star. Kepler's primary goals are to determine how abundant planets are in our galaxy, what the distribution of sizes and orbits of those planets are, and, ultimately what fraction of stars might harbor potentially habitable, Earth-sized planets.

As of January 2013, Kepler has identified over 2,700 planet candidates, of which over 350 are nearly the same size as the Earth. In addition, there are 816 "Super Earth"-sized planets, planets intermediate in size between the Earth and the planet Neptune—as well as 1,290 Neptune-sized planets; 202 Jupiter-sized planets, and 81 "Super-Jupiter"-sized planets. More than 50 of Kepler's planet candidates orbit in the habitable zone of their host star-- the range of distances from a star where the surface temperature of an orbiting planet might be suitable for liquid water.

NASA's most recent discovery, announced just a few weeks ago, is two new planetary systems that include three super Earth-size planets in the "habitable zone" of their stars. The first system, known as Kepler-62, has five known planets: 62b, 62c, 62d, 62e, and 62f. The second system, Kepler-69, system has two known planets: 69b and 69c. Kepler-62e, 62f, and 69c are the super Earth-sized planets, with diameters just 1.6x, 1.4x, and 1.7x that of the Earth, respectively. The host star of the Kepler-69 system belongs to the same class of stars as our sun, called G-type. It is 93 percent the size of the Sun and 80 percent as luminous and is located approximately 2,700 light-years from Earth in the constellation Cygnus. The host star of the Kepler 62 system is a smaller, cooler K-type star, just 2/3 the size of the Sun and only 1/5 as bright. These exciting discoveries illustrate that we are another step closer to finding a world similar to Earth around a star like our Sun.

Kepler is teaching us that the galaxy is teeming with planetary systems, and giving us hints that nature makes small planets efficiently. Having completed its prime mission, and now some 5 months into its extended mission, the Kepler spacecraft is starting to show its age. We do not know how much longer it will be able to maintain the very precise pointing required for its exoplanet mission, but we do know that Kepler's legacy is secure. It has been a pioneer in expanding our understanding of exoplanets and stellar seismology and its rich legacy will serve as a solid foundation upon which future missions will build.

Along with Kepler, NASA's Hubble and Spitzer Space Telescopes have also successfully detected the feeble signature of an exoplanet in the overwhelming glare of its host star. Specifically, scientists have used the Hubble Space Telescope to measure the absorption of hydrogen, carbon, oxygen, carbon dioxide, and water vapor in the boil-off from the atmosphere of two transiting Hot Jupiter exoplanets. These large, gaseous giant planets are easier to detect due to their size and very short orbital periods. Also, scientists have used the Spitzer Space Telescope to measure the infrared light from a Hot Jupiter exoplanet and used that to make a temperature map of the planet's atmosphere and determine that the planet is whipped by ferocious winds.

Future Exoplanet Exploration Missions

Moving forward from the current exoplanet missions in operation and development, NASA recently selected a new mission, the Transiting Exoplanet Survey Satellite (TESS), as part of its Explorer Program. Planned to launch in 2017, TESS will undertake a two-year, all-sky search for transiting exoplanets around the nearest and brightest 500,000 stars. While Kepler has taught us about the abundance of planets of all sizes in one particular region of our galaxy, TESS will reveal the exoplanets that are nearest to our Solar System. TESS is expected to discover thousands of new planets – including Earth-sized, rocky planets – and those systems will be ideal candidates for characterization by future missions such as JWST and a wide-field infrared survey telescope.

Building on the pioneering observations of the Hubble and Spitzer Space Telescopes and the exoplanet surveys of Kepler and TESS, JWST will use transit spectroscopy to determine atmospheric and physical properties of planets ranging in size from Jupiters to super Earths; it will be able to study the composition, chemistry, and physical conditions of exoplanet atmospheres. Additionally, JWST will use direct imaging to find and study young (i.e., still warm) Jupiters and Saturns as well as rings of dust, and icy/rocky planetessimals (asteroid and Kuiper Belts) in many exoplanet systems.

Beyond JWST, a wide-field infrared survey telescope would complement Kepler's exoplanet census by finding thousands of planets down to Earth-size that orbit either in or outside of the habitable zone of their star. NASA is studying such a mission. As part of that study, NASA is also studying the use of an existing large space telescope system and the addition of a coronagraph capable of studying the atmospheres of exoplanets around other stars through direct imaging. By providing the first opportunity for in-space operations of a high-contrast coronagraph, such a mission would lead the way toward a future telescope capable of characterizing in detail Earth-like planets around other stars and searching for evidence of life beyond our Solar System.

NASA is aware that exoplanets are of great interest to the entire science community and the general public. The science of exoplanets brings together many scientific disciplines. That is one reason why all of the data from NASA's space telescopes, including Kepler, Hubble, and Spitzer, is made openly available for analysis by scientists other than the members of the science teams for those telescopes. This has resulted in an explosion of discoveries about exoplanets, including some of the discoveries already mentioned. For citizen scientists, PlanetHunters.org offers a web site where anyone can search through Kepler data and discover exoplanets. So far, over 18 million observations have been analyzed, and 34 candidate planets had been found. In October 2012 it was announced that two volunteers from the Planet Hunters initiative had discovered a novel Neptune-sized planet which is part of a four star double binary system. This is the first planet discovered to have a stable orbit in such a complex stellar environment.

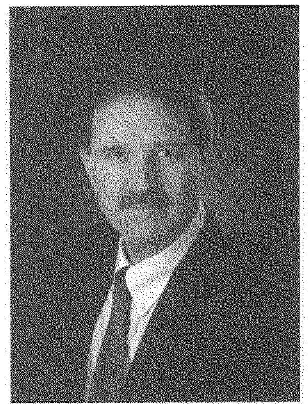
Exoplanet Technology Development Infrastructure

To make the exoplanet discoveries possible, and to reduce both the risk and cost of future exoplanet exploration missions, NASA is investing in exoplanet detection technology. NASA has developed high contrast imaging testbeds, an advanced visible nulling testbed, deformable mirrors for ultraprecise wavefront control, and a vacuum surface gauge for surface characterization and deformable mirror calibration. Moreover, NASA has computational models and software including coronagraph modeling tools, integrated thermo-optical-mechanic modeling tools, and generalized error-budgeting tools to design space-based telescopes and instruments capable of detecting and studying exoplanets.

Conclusion

NASA has in place a comprehensive program to detect and characterize exoplanets. With the progress we have already made, I am confident that it is not a question of whether or not we will find an Earth-like exoplanet, but when. With our programs, the active participation of a rapidly growing scientific community, and our partners, we will continue to make major strides forward in our understanding of the science of exoplanets. It is programs like Kepler that capture the imagination of everyday people, including our students of today who will be the scientists and engineers of tomorrow. NASA has exciting missions such as JWST, TESS, and the wide field infrared survey telescope after Kepler to reach even farther back in time, to explore other regions of the universe, and to start characterizing and analyzing the atmospheres of exoplanets. The future of exoplanet research is bright, and NASA will continue to play a leadership role in that future. I look forward to answering any questions you may have.

Dr. John M. Grunsfeld, Associate Administrator



Dr. John M. Grunsfeld was named Associate Administrator for the Science Mission Directorate at NASA Headquarters in Washington, D.C. in January 2012. He previously served as the Deputy Director of the Space Telescope Science Institute in Baltimore, MD, managing the science program for the Hubble Space Telescope and its partner in the forthcoming James Webb Space Telescope. Dr. Grunsfeld's background includes research in high energy astrophysics, cosmic ray physics and in the emerging field of exoplanet studies with specific interest in future astronomical instrumentation.

John Grunsfeld joined NASA's Astronaut Office in 1992. He is veteran of five space shuttle flights, having visited Hubble three times as an astronaut, performing a total of eight spacewalks to service and upgrade the observatory. He logged over 58 days in space on five shuttle missions, including 58 hours and 30 minutes of spacewalk time. He first flew to space aboard Endeavour in March 1995 on a mission that studied the far ultraviolet spectra of faint astronomical objects using the Astro-2 Observatory. His second flight was aboard Atlantis in January 1997. The mission docked with the Russian space station Mir, exchanged U.S. astronauts living aboard the outpost, and performed scientific research using the Biorack payload. Dr. Grunsfeld flew on three more shuttle missions - Discovery in December 1999, Columbia in March 2002 and Atlantis in May 2009 -- that successfully serviced and upgraded the Hubble Space Telescope. He served as the payload commander on the 2002 mission and lead spacewalker in charge of Hubble activities on the 2009 flight. In 2004 and 2005, he served as the commander and science officer on the backup crew for Expedition 13 to the International Space Station.

Dr. Grunsfeld graduated from the Massachusetts Institute of Technology in 1980 with a bachelor's degree in physics. Returning to his native Chicago, he earned a master's degree and, in 1988, a doctorate in physics from the University of Chicago using a cosmic ray experiment on space shuttle Challenger for his doctoral thesis. From Chicago, he joined the faculty of the California Institute of Technology as a Senior Research Fellow in Physics, Mathematics and Astronomy

For Grunsfeld's NASA astronaut biography, visit: http://www.nasa.gov/home/hqnews/2011/dec/HQ_11-396_Grunsfeld.html http://www.jsc.nasa.gov/Bios/htmlbios/grunsfel.html

For more information about NASA's Science Mission Directorate, visit: http://nasascience.nasa.gov

Chairman PALAZZO. I now recognize our final witness, Dr. Ulvestad.

TESTIMONY OF DR. JAMES ULVESTAD, DIRECTOR, DIVISION OF ASTRONOMICAL SCIENCES, NATIONAL SCIENCE FOUNDATION

Dr. ULVESTAD. Good morning, Chairman Palazzo and Chairman Bucshon, Ranking Members Edwards and Lipinski, and Subcommittee Members. Thank you for giving NSF the opportunity to speak to you today about our support of exoplanet research.

For millennia, people have looked up in the sky and wondered if there is other life out there, if there are other people out there. Determining if there were other planets around other stars was really something that couldn't be done for almost 400 years after Galileo first turned his telescope to the heavens. So when I was in graduate school at Maryland in the late 1970s, early 1980s, we never would have dreamed that we could be at the place where we are now speaking about Earth-like planets. But just 20 years after the first detection of planets around other stars, we are now seriously talking about Earth-sized planets in the habitable zones of other solar systems, which I think is quite spectacular.

NSF has supported exoplanet research since its infancy. The first detections were made actually with NSF's Arecibo radio telescope in 1992 and it was very surprising to find planets around a compact star called a neutron star, which was not where people were looking. So I think exoplanet research over the 20 years since then has been full of surprises—planets much, much bigger than Jupiter very, very close to their stars, and these surprising outcomes have totally revamped the way we think about solar systems and the way planets form.

At NSF, the exoplanet research that we fund relies on three critical elements: investigators, that is, people; tools, that is, telescopes; and technology development. So we presently have more than 40 active awards to individual investigators who are doing exoplanet research, and many of these are people just beginning in our field. There are early career awards, there are postdoctoral fellowships, and this field is so exciting that a lot of the young people who are going into the field of astronomy actually want to work in this area. With our international partners, we provide the ground-based telescopes that complement the space-based telescopes that Dr. Grunsfeld has mentioned that are needed to make precision measurements of planetary systems. And third, and not to be neglected, we support technology development that is very important for getting us to the stage where we can detect planets as small as the Earth. For example, we support technology development that can be used to get more accurate wavelength standards that enable precision measurements of stars to determine motions that are being caused by planets with masses as low as the Earth.

As exoplanet science enters its third decade, we are growing beyond just the counting of planets. Dr. Grunsfeld mentioned more than 800 or 900 confirmed planets but now we are funding research at NSF into characterizing planetary properties, into measuring exoplanet atmospheres, and into the formation and evolution of planetary systems. Starting next year, a new $25 million instrument on our Gemini telescope in the South will be used to image up to 600 other nearby stars, trying to image planets. This instrument cannot image planets right next to the star but out at the distance of Jupiter and beyond.

Over the last four years, NASA's Kepler satellite, as mentioned previously, has opened these wonderful new opportunities, and just to mention the complementary science, some of the recent discoveries have actually been made using Kepler data by investigators that NSF funds. We have an NSF early career investigator who helped develop the technique that was used to detect these two planets, Kepler-62e and f, that are thought to be in the habitable zone around Kepler-62.

We are in the process of completing a very large instrument called the Atacama Large Millimeter Array, which was dedicated in Chile two months ago, and this, even in its pre-dedication phase, has detected the presence of Earth-mass planets around the bright star Fomalhaut, which you can see with your naked eye in the night sky just 25 light-years away. ALMA will in fact be incredibly complementary to the James Webb Space Telescope, with James Webb in the near infrared, and with ALMA in the far infrared, both imaging dust shells and circumstellar discs around nearby stars at approximately the same resolution. As with all of NSF's major facilities, the data acquired with these instruments will be available to all investigators, not just to the people who propose to get the data.

One of the key goals of NSF's strategic plan is to transform the frontiers of science and engineering, and we think that since the very first exoplanet detections, NSF-funded research has transformed the frontiers of exoplanet research. We will be very interested to see how the frontiers continue to be transformed over the next 20 years.

Mr. Chairman, this concludes my remarks, and I would be happy to answer any questions you and the Subcommittee Members might have.

[The prepared statement of Dr. Ulvestad follows:]

Statement of

Dr. James S. Ulvestad
Division Director, Division of Astronomical Sciences
Directorate for Mathematical and Physical Sciences
National Science Foundation

before the

Committee on Science, Space, and Technology
Subcommittee on Space
And the
Subcommittee on Research
U.S. House of Representatives

May 9, 2013

Exoplanet Discoveries; Have We Found Other Earths?

Good morning Chairman Palazzo, and Chairman Bucshon, Ranking Members Edwards and Lipinski, and members of the Subcommittees. My name is Jim Ulvestad, and I am the Division Director for Astronomy in the NSF Directorate for Mathematical and Physical Sciences. Thank you for giving NSF the opportunity to speak to you about our support of extrasolar planet, or exoplanet, research. This is one of the most exciting areas of astronomical discovery that we support today. It has been recognized by the most recent National Academy of Sciences decadal survey in astronomy and astrophysics as an area that is ripe for new discoveries over the next decade, and one whose excitement we are pleased to share with our colleagues at NASA, with the scientific community, and with the American public.

For centuries, and perhaps millennia, humans have looked up into the sky and wondered if we are alone in the universe. A first step in answering that question is to determine if there are planets orbiting other stars, a goal that remained unachievable for nearly 400 years after Galileo turned his telescope to the heavens. Technological developments beginning in the 1980s finally made it possible for astronomers to actually detect planets outside our solar system, and the first discoveries of such exoplanets were made in the 1990's by NSF-funded astronomers. Exoplanet science has progressed rapidly, to the point where 20 years after the first discoveries, there are more than 700 confirmed exoplanets, and thousands more candidates have already been identified by NASA's Kepler satellite. We are entering a scientific era in which we have the capability to detect not only giant planets the size of Jupiter, but Earth-sized planets in the habitable zones of their solar systems, the locations where liquid water can exist.

NSF has supported this field since its infancy. The first definitive detection of an exoplanet was made in 1992 by an astronomer at NSF's Arecibo Observatory collaborating with a postdoctoral researcher at NSF's Very Large Array. Dr. Alex Wolszczan and Dr. Dale Frail used the Arecibo radio telescope in Puerto Rico to uncover the presence of two planets orbiting a pulsar, which is a dense neutron star totally unlike our Sun. This discovery was a surprise to the astronomical community, which had expected planets around "normal" stars and not around ultra-dense stellar remnants. Surprise turned out to be a hallmark of the first 20 years of research on exoplanets. Our best understanding of how solar systems form and evolve was challenged and had to be revised in light of the new discoveries made by the scientific process.

Planets orbiting Sun-like stars were detected soon after the first pulsar planets, with the surprising outcome that planets more massive than Jupiter were found in orbits very close to their parent stars. NSF has funded these transformative efforts for more than two decades, with research grants resulting directly in the first detection of multi-planet systems, the first detection of exoplanets with masses as small as that of Saturn, and the first planets detected using the technique of gravitational lensing of the radiation from background stars.

NSF-funded research on exoplanets relies on three critical elements: investigators, tools, and technology development. First, NSF funds the core scientific research of individual investigators; NSF presently has more than 40 active awards to individual investigators and small teams pursuing exoplanet research, including highly competitive awards to young scientists in the ascending stages of their careers. Second, together with our international partners, NSF provides the tools that astronomers need to make precision measurements of planetary systems; the newly inaugurated Atacama Large Millimeter/submillimeter Array (ALMA) can study planets in the act of formation, while the Gemini Observatory is poised for new exoplanet discoveries with the Gemini Planet Imager (GPI) that will be commissioned in the next year. Third, NSF supports the technology development that will enable the detection of planets as small as the Earth. In total, NSF currently invests approximately $10 million per year in exoplanet research. Roughly half of this amount is spent on individual investigator research grants, and the other half on the development and operation of advanced-technology telescopes.

As exoplanet science enters its third decade, we are growing beyond the mere counting of planets and beginning to investigate and understand their physical characteristics. At NSF, we are funding research into the observational characterization of planetary properties, measurements and models of exoplanet atmospheres, and the theory of the formation and evolution of planetary systems. With our international partners, we are poised to take the next step with the $25 million GPI mentioned earlier. This instrument will combine advanced adaptive optics to correct for the blurring effects of Earth's atmosphere, a coronagraph to block the glare of the parent star, and advanced spectral capabilities to image exoplanets and study their chemical compositions. Starting in 2014 a US-led team will begin a GPI survey of up to 600 nearby stars, which will provide family portraits of dozens, if not hundreds of other planetary systems.

Meanwhile, NASA's Kepler satellite has opened wonderful opportunities over the past four years, and we are all very grateful to NASA and the Kepler team for the advances they have enabled in exoplanet research. NSF-funded scientists have taken full advantage of the Kepler data; in recent months, Earth-sized planets have been confirmed in the habitable zone of the Kepler-62 stellar system. This exciting discovery was made using a technique developed by Dr. Eric Agol of the University of Washington, with funding he received from an NSF early-career award made in 2006. An NSF Graduate Research Fellow at the University of California, Mr. Erik Petigura, leading another recent study using Kepler data, has concluded that approximately 15 percent of Sun-like stars have Earth-sized planets in close-in orbits. This implies that many such stars also will be found to have Earth-sized planets in their habitable zones.

We stand at the threshold of many exciting discoveries over the next decade, as the worlds of science fiction become part of scientific reality. In 2013, the number of proposals for exoplanet research received by the NSF increased to more than 100, from a number of 20-25 proposals per year just eight years ago. NSF is able to fund only a small fraction of those proposals, but we expect them to give rise to more exciting discoveries. For example, while still in its scientific checkout phase, scientists using ALMA have found evidence for Earth-mass planets around nearby stars; as it nears its full complement of 66 antennas, ALMA will deduce the presence of many more exoplanets and study the chemical composition of the planetary nurseries. Over the next 3 to 5 years, studies like the ones done with ALMA will be complementary to the expected frequent releases of exoplanet images and spectra from Gemini as the GPI instrument comes on line. As with all of NSF's major facilities, the data acquired with these instruments will be freely available to all researchers after an initial proprietary period.

Where will we be 20 years from now? We will have dozens, probably hundreds of Earth–sized worlds detected and imaged in our region of the Galaxy. We will have an accurate knowledge of the fraction of nearby stars with planets of all sorts, and of those with Earth-sized planets. We will have images of solar systems like our own, including other Earth-like planets. We will have information about the chemical compositions of many of these planets and we will be searching the data for biosignatures, or evidence of life. These discoveries will continue to change our understanding of how planetary systems like our own form and evolve, and of humanity's place in the universe.

Summary

One of the key goals of NSF's strategic plan is to "Transform the Frontiers" of science and engineering. Since the very first discoveries of exoplanets 20 years ago, NSF-funded research has transformed the frontiers of exoplanet research, enabling us to address a fundamental question: "Are there other places out there where life could exist, and what kind of life is there?" Because the people of the United States value knowledge and discovery, we continue to understand more and more about the possibilities of life elsewhere, and can only await the fabulous new discoveries of the next 20 years.

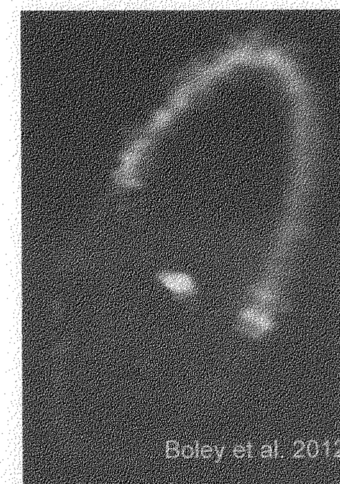
Mr. Chairman this concludes my remarks. I would be happy to answer any questions you may have.

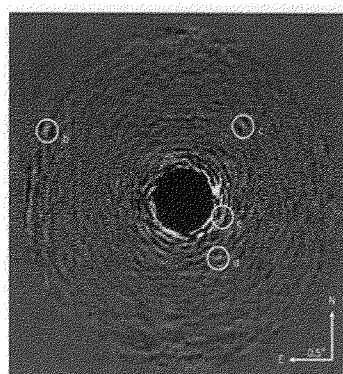
Biography – Dr. James S. Ulvestad

Dr. James S. Ulvestad is the Division Director of the Division of Astronomical Sciences at the National Science Foundation, a position he has held since 2010. Previously, he was an Assistant Director of the National Radio Astronomy Observatory (NRAO), where he was in charge of the Very Large Array and Very Long Baseline Array radio telescopes, and later was the head of the NRAO New Initiatives Office. Before his time at NRAO, Dr. Ulvestad served in various capacities at the NASA Jet Propulsion Laboratory, where he played important roles in several interagency and international programs. Among his community service activities, Dr. Ulvestad chaired the Demographics Study Group of the 2010 National Academy of Sciences decadal survey in astronomy and astrophysics, was an elected member of the American Astronomical Society Council, and has been a member of NASA's Structure and Evolution of the Universe Subcommittee. Dr. Ulvestad is an author or co-author of more than 80 refereed papers in the scientific literature, as well as numerous technical reports.

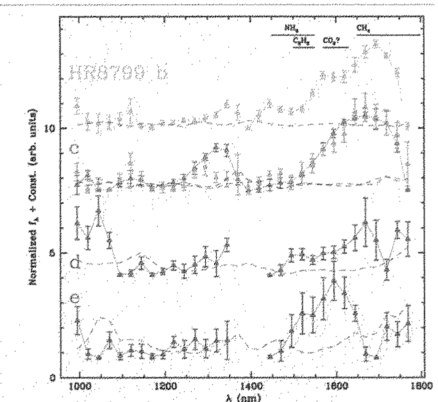
ALMA

- ALMA was inaugurated March 13, 2013
- Early ALMA image of debris disk around Fomalhaut shows narrow dust ring, modeled to be shepherded by two Earth-mass planets





Monitoring Cloudy Skies on Extrasolar Planets



- Spectra of four exoplanets observed simultaneously for the first time: HR 8799 (Oppenheimer et al. 2013, AST-0908484).
- Data show methane and ammonia molecules present at levels consistent with dynamical changes in the clouds (→weather?)
- Atmospheric changes can now be tracked over time on extrasolar planets.

Chairman PALAZZO. I thank the witnesses for their testimony, reminding Members that Committee rules limit questioning to five minutes. The chair will at this point open the round of questions. The chair recognizes himself for five minutes.

Dr. Grunsfeld, 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-lift launch vehicle such as the Space Launch System is needed to launch a telescope this size. How does the development of the SLS enable future exoplanet discoveries?

Dr. GRUNSFELD. The Space Launch System, our large rocket in development, has the characteristic of course that it can lift heavy weights but almost of equal importance for science is that it has a very large launch route and so a future telescope that would have the light-gathering capability to detect and measure the bioscience, if you will, of a very, very dim planet around a very bright star will require a lot of collecting area and advanced instrumentation, and such a large telescope if you think about how James Webb Space Telescope is going to launch, and I know Chairman Smith, you have seen the model, that all gets folded up like origami and transformed into a launch route of an Orion V rocket, very big. That is about the largest thing we can put into space in a conventional rocket. The Space Launch System is transformative and this very large launch route would enable us to scale that up to something that would be a telescope that could detect life around a nearby Earth-like planet. So we are looking very favorably on the development of SLS.

Chairman PALAZZO. Also, Dr. Grunsfeld, how does NASA plan to manage education and public outreach related to exoplanet discoveries in the wake of the proposed reorganization of education and outreach funding? Are there any anticipated changes to the education and public outreach strategy? And how would the proposed reorganization impact the inspiration of the next generation of explorers?

Dr. GRUNSFELD. Well, the first thing that I will say is that the critical component in the inspiration of our next generation of explorers, scientists, engineers and even more important, to have a very broad educated populace in the scientific method and basic science is to do exciting things that produce exciting scientific results that we can then get out into the public domain. That is the number one requirement, and on that scale, we are changing nothing. NASA is going to continue working with NSF and the rest of the scientific community to try and make exciting discoveries. I think when we find a rocky planet around a nearby star that we think is very Earth-like, that is going to be incredibly exciting, and if we are so lucky to detect life on a planet like that, I think it will be transformative to humans here on Earth.

As far as our NASA education, the President's Fiscal Year 2014 proposal to consolidate the science, technology, engineering and mathematics education infrastructure from a number of agencies into three primary agencies, NASA is part of that plan and so our education activities will be transferred and the budget with them will be transferred to a combined Department of Education, Smithsonian and National Science Foundation architecture. That plan is still in development. Clearly the Administration has as its intention that this will strengthen the STEM education in our country. One of the things that I am very proud of is that our science missions and the scientists who do that work spend time currently reaching out to master teachers, to pre-service and in-service teachers and all the way through students, and so whatever plan emerges from this new reorganization it is critical that we preserve that connection with the great science.

Chairman PALAZZO. And my final question is for Dr. Grunsfeld. The National Academies issued their Decadal Survey, New Worlds, New Horizons, that laid out the path forward for astronomy and astrophysics. How does NASA plan to adapt its plans for exoplanets now that we are facing a tougher budgetary environment?

Dr. GRUNSFELD. Well, I did bring a graphic. I don't know if that is easily available to come up. We have in our current portfolio of exoplanet research, and again, it is all done in concert with National Science Foundation but also private observatories, but we use ground-based observatories, currently Hubble, Spitzer and Kepler, to investigate exoplanets. So that is our current stable of very powerful telescopes, and that is what has allowed us to make all this tremendous progress, as well as other ground-based observatories.

The Transiting Exoplanet Survey Satellite was selected out of our competitive program but it does advance us quite significantly in exoplanet investigations in that it will find all of the closest transiting exoplanets, and that will allow us to use both ground-based and space-based observatories to start characterizing the nature of these planets, even down to measuring the atmospheres of the planets around these nearby stars. If we find something like an Earth, that will allow us to start looking for signs, even with James Webb Space Telescope, of water in the atmosphere, and if you have water in the atmosphere of a rocky planet in the habitable zone, that means there is probably lakes and clouds and precipitation. That gets us a long way towards that question of could there be life.

Next, of course, is James Webb Space Telescope. The next two that are kind of dim are addressing what is in the New Worlds, New Horizons, and so the first one is an Astrophysics Focused Telescope Asset. That is just code for a study we are doing, which is to use the 2.4-meter optic system that we received from disposition of a National Reconnaissance Office asset, and we are looking at that as a wide-field telescope that meets the WFirst science requirements and with the addition of a coronagraph, something that blocks out the light of the central star, would allow us to study nearby exoplanets in greater detail than we could have ever done with anything we have currently on the plate.

Then beyond that, the New Worlds Telescope—that is just how it was described in the Decadal Survey—would be this very large telescope, something where the James Webb Space Telescope is 6–1/2 meter diameter, about 20 feet, in order to actually detect life signs, if they are there, of a planet around a relatively nearby star, we would probably have to go to 16 or 20 meters in diameter, and that is the one that was referenced in your Space Launch System question.

So we have studies going, technology work on prototype detectors per those future lines. Given the constrained physical environment, we are looking very closely at this NRO asset as a way to bring down the cost of doing the next great astrophysics mission.

Chairman PALAZZO. Thank you, Dr. Grunsfeld. I now recognize Ms. Edwards for five minutes.

Ms. EDWARDS. Thank you very much, and thanks to our witnesses. I have to say, the work that you do is among the most exciting that those of us who are laypeople can think about. It truly is, and so thanks so much for everything that you do.

Dr. Grunsfeld, I want to follow up with your last response, and it really does have to do with this constrained fiscal environment because a number of the things that each of you has laid out requires an allocation of resources over a period of time for us to get on with, if you will. And so I wonder if you can tell me how the current budget environment is really affecting exoplanet research and the additional technologies that are going to be needed over this next decade, and what are the likely impacts if we should continue with sequester into Fiscal Year 2014?

Dr. GRUNSFELD. So there is no question that the budget environment has caused us to have to make some tough choices, and whenever we try and make those tough choices, we think about balance, we think about scientific priorities, and in the case of exoplanets we are very fortunate that we have high-value observatories on orbit, and so one of the things we have to prioritize is what are we going to keep operating on orbit providing high scientific return. The latitude we have for adjusting to a changing budget is really in the start of new projects, and so as an example, even though we have selected the Transiting Exoplanet Survey Satellite, TESS, we have had to slow the start of that mission by about six months, just what we have seen from this year and looking into Fiscal Year 2014. If we continue into a sequestered environment, then we are going to have to look at perhaps turning off an operating observatory or cutting back further on the development of new missions, and something like the study for the NRO Asset Telescope, AFTA, you know, we would have to reduce our investment in that future, which would of course slow that down further.

Now, we haven't—that is a study. We haven't approved or come to you to ask for approval either. That is not approved internally within NASA or externally. We are just looking at the feasibility right now on that. But it would slow down future development.

Ms. EDWARDS. Dr. Ulvestad?

Dr. ULVESTAD. Yes, I would say there are two primary issues that we would have to think about in terms of the constrained fiscal environment. One is that some of the new observatories that I spoke about are more expensive to operate than the older observatories that we used to have, and so in a constrained environment, in order to operate those new tools, what sometimes has to give in the short term is the research grants to individual investigators. As an example, I will cite the ALMA Telescope, which we are just bringing online, which we expect to be used very strongly in conjunction with JWST. So I will just mention that. That is actually one of the ways that we will maximize the sciences by trying to have these space and ground assets work together on coordinated programs. But one of the issues that we will run into for ALMA, which is an international telescope, is that if we are not able to fund our investigators to do the research and to bring their postdocs and graduate students in, some of the best exoplanet science with that telescope might be done by our international partners and not by the U.S. investigators. So I think that is a very serious concern for us.

The concern other than that is just being able to make sure that having invested lots of money in these big tools that we are able to operate them adequately, that we don't start doing things like scrimping on the infrastructure because we are trying to save a little bit of money here and there and then essentially causing damage to the big investments we have already made.

Ms. EDWARDS. Well, let me follow that up, because it is one of the concerns I have had, for example, with James Webb Space Telescope is that we actually got a lot of extended lifespan out of the Hubble because a lot of upgrades were made over a period of time and so that gave us a tremendous bang for the buck. But the question is whether if we face future delays into 2018 will we, beyond then, be able to get more bang for the buck out of JWST in the same way that we did out of Hubble.

Dr. GRUNSFELD. Quite a long time ago, we looked at making the James Webb Space Telescope serviceable similar to the Hubble, and largely due to the fact that it is an infrared telescope and it has to be very, very cold, its design was to put it a million miles away from Earth, and that is a very inaccessible place, and so we abandoned the idea of visiting it and upgrading it. So the James Webb Space Telescope doesn't have the capability for upgrades the way Hubble does. So what determines the James Webb Space Telescope lifetime is really the onboard fuel, and so we have designed it to a design requirement of five years. At NASA we have redundancy, we have reserves, you know, we plan for failures and operations. We hope, and actually the engineering says we should get 11 years of life out of the James Webb Space Telescope in an actual operational mode that we think we will use.

Given that framing, we are looking very closely, and I am very excited about the partnership observatories likes the Atacama Large Millimeter Array because that is the way we are going to maximize the output of the James Webb Space Telescope is by using our other assets. I have a little bit of a dream, but that dream is that not only will we have the ALMA and the James Webb Space Telescope, that we will also have some overlap with the Hubble Space Telescope, and engineering mechanics will determine that lifetime but right now Hubble is still doing well.

Ms. EDWARDS. Thank you.

Chairman PALAZZO. I now recognize Mr. Bucshon for five minutes.

Mr. BUCSHON. Thank you, Mr. Chairman. I am going to make a comment first and then a couple of questions.

This is not the only hearing that we have heard from people who depend on so-called discretionary spending at the Federal level, and my comment is, is that until the American people can help us address the entire piece of the Federal spending pie, of which 60 percent we are not addressing today in Washington, D.C., people who depend on discretionary spending are going to continually feel the pinch, which is problematic, as Ms. Edwards pointed out. At this point there is really only one significant proposal in Washington, D.C., to address the 60 percent of the pie that is on our side of the aisle in our budget, and until the American people help us address that, we are going to continue to have ongoing discretionary-funding problems because most of the driver of our national debt is not in discretionary programs, it is in mandatory spending, and everyone in D.C. recognizes that as a major issue.

The question I have, the first question I have is, I guess any one of you can address it, and I think it is important when people like me go back to Indiana and talk to people about where we spend money and why, and so Dr. Grunsfeld, in short order, what can I tell people why what you are doing is important to the American people?

Dr. GRUNSFELD. Well, there are a couple of different levels but I will try and keep it short. The first is that investments in NASA and the National Science Foundation in basic research is really the investment in our future, and it is not an abstract thing. Vannevar Bush and the Endless Frontier, the document that helped spur on the creation of the National Science Foundation really queued it up as our investigations in basic science are what are critical to our economic prosperity, our health care and the future of the country, and it is just a wonderful document to read because that is coming out of World War II, and the question was asked, how did science help us win the war, and then generate such a strong economy. If we start cutting back on the basic research, on trying to solve very hard problems like how to build the instruments on James Webb Space Telescope that challenge our industry, that challenge our engineers, that allow these companies to grow new techniques and new competitive tools, we will just continue to start losing ground on the kinds of innovations that drive our economy, and that is a very tight loop and well-documented loop.

At the other end of the extreme is this idea of kids looking up in the night sky, and I think we have all done that, and the science tells us things that just inspire us, that cause us to want to look towards the future, to have vision, that drives people through hard times and that makes it into the science textbooks that hopefully our students then bring with them as they become future decision makers in our country, not just in Congress but as medical doctors, and most importantly, as parents of children, that they have the knowledge to make good decisions based on technical knowledge. Thank you.

Mr. BUCSHON. Okay. I assume everyone is going to have a similar response because I have another question that I want to ask. By the way, I agree with you. I think that when I talk to people about NASA, and this comes up all the time, I pull out the list of things that have been developed technologically and innovations that have come through NASA that aren't just about putting a person flying around the Earth and going to the moon but all the other things that happened as a result of developing the technology to make that occur.

My second question is, I am always interested when I see—and I hate to focus on NASA—like our project on Mars is that we are looking for water, we are looking for carbon-based life forms, and there are other—that is our definition of life, so to speak. Are there other people out there that have other definitions of life that are looking at that we might also be exploring for?

Dr. GRUNSFELD. Well, I think that is a good question for Dr. Doyle from the SETI.

Mr. BUCSHON. That would be great.

Dr. GRUNSFELD. I will say that the Curiosity Rover, although it has the scientific instruments, the mass spectrometers to look at all the components of the soil we are digging up and looking for some signs of perhaps previous carbon stuff going on, it would see many other things, but I will pass that to Dr. Doyle.

Dr. DOYLE. I will just say the definition, some of the people working in the field of exobiology are looking at the definition of life as anything that can store information. So there is a broad brush there. So there are studies going on about a broader definition. Right now you have to work with what you know, but silicon-based information storage and crystals and so on has not been out of the realm of consideration.

Mr. BUCSHON. Thank you. I yield back.

Chairman PALAZZO. I now recognize Mr. Lipinski for five minutes.

Mr. LIPINSKI. Thank you, Mr. Chairman. I just want to start out by asking Dr. Grunsfeld about the status of the decision on what to do with the telescopes donated by NRO. You had mentioned them, but has that all been determined what is going to be done with those?

Dr. GRUNSFELD. So the answer is no, we haven't determined what is going to be done with those. That is the subject I was talking about of the Astrophysics Large Focused Telescope Asset that we have done a study on. At the end of this month, I will get the results of that study and then we will brief Administrator Bolden, and that would us to go to the next step from just the study phase to actually, if he approves it, seeing if we should start doing some engineering to validate that those telescopes could actually be used for a future space telescope. So, right now our focus is on completing the James Webb Space Telescope. As we get further into development of that telescope, then we could start seriously thinking about building another mission of some kind, whether in astrophysics or another area. We are very excited about what we are seeing so far, and I am happy, once Charlie Bolden, our Administrator, has dispositioned it, to come back and talk to you about it.

Mr. LIPINSKI. Very good. I want to ask all the panelists, what, if anything, is needed to further facilitate the coordination and collaboration between the NSF and NASA on exoplanet exploration and research? Is there anything more that would help? Any places for improvement that you see?

Dr. ULVESTAD. Let me start with that. I think that as you heard from our testimony, we understand very well how our different assets could work together with each other, and we are in pretty regular communication about setting up joint programs and so on. In fact, I think one of the key elements is actually even working at a lower level, which is that our program officers in the two agencies actually talk to each other regularly. We had a meeting of all of our program officers in our Astronomical Sciences Division and NASA's Astrophysics Division about a month and a half ago just to talk about making sure that we kept our lines of communication open, making sure that we understood which proposals we were getting and they were getting for research so that we were doing complementary things and not doing duplicative research. I think that is a very important aspect of our coordination, to maximize the efficiency of the funding. I would say that it is not clear to me that we need a lot of help as long as we keep talking to each other, which we are doing very regularly right now. So I will yield to Dr. Grunsfeld and see what he would like to say about that.

Dr. GRUNSFELD. I would concur on that. I wouldn't take this too far but I think one of the effects of always being budget limited for research in space astronomy and ground-based astronomy is that you are forced to be very communicative and creative with your partners to make sure that you don't have duplication because there isn't enough money to be able to duplicate things. In the case of the National Science Foundation and the NASA efforts on exoplanets, it is a very nice division because we use basically the space-based and ground-based as the first natural breakpoint.

Mr. LIPINSKI. Thank you.

Dr. DOYLE. I would just say that SETI Institute is a nonprofit and there are many research institutions that are rather small, but they have started up support of exoplanet research. For example, Planet Hunters has millions of people that go home at night and start looking for planets. So there is this huge upswell of millions of supporters of exoplanet research that is also in kind of the nonprofit realm as well that could be tapped.

Mr. LIPINSKI. That is always good to hear. I know we have a lot of Members here and a short time, so I will yield back the rest of my time. Thank you.

Chairman PALAZZO. I now recognize Chairman Smith for five minutes.

Chairman SMITH. Thank you, Mr. Chairman.

Actually, my first question, I think, has largely been answered, and it was, how do we expedite the process of searching for exoplanets, and it sounds to me like we need to stay on track with the exoplanet missions that Dr. Grunsfeld highlighted a while ago. Would you all agree, Dr. Doyle and Dr. Grunsfeld, that the first thing we need to do is make sure the current missions that have been proposed are funded and not all had been funded? Would that be your recommendation?

Dr. GRUNSFELD. Well, I am glad to say that——

Chairman SMITH. Or are there any other missions that we ought to consider?

Dr. GRUNSFELD. So I agree with you completely. The plan we have is, I think, the best plan that we could have and the Administration's proposal for Fiscal Year 2014 funds us to go on with the next mission, which is the Transiting Exoplanet Survey mission, and fully funds James Webb Space Telescope. All of that said, ultimately nature will determine when we find the first planet that looks just like Earth.

Chairman SMITH. And Dr. Doyle, are there any other missions we should be considering other than the ones that need to be funded?

Dr. DOYLE. Well, I think the ones currently are quite well planned. They do an all-around survey, and then to follow through with detecting exolife basically. So I think we are on track.

Chairman SMITH. Dr. Grunsfeld, I was going to point out, I think when you quoted Alfred Lord Tennyson, you didn't realize that we had the quote that you mentioned on the wall behind the podium, or did you notice that?

Dr. GRUNSFELD. I noticed that in 2003 when I was Chief Scientist, and that is when I started putting it into my presentation.

Chairman SMITH. Good. Then we came first. As you know, it is a long poem, and that is the refrain that is repeated throughout the poem, so it really has a good impact.

Dr. Ulvestad, you mentioned our international friends and the missions that they have initiated. Do you think we should perhaps duplicate some of those missions or should we rely upon information that we get from them?

Dr. ULVESTAD. Well, I think that what we are doing right now with our international colleagues is, we are not doing duplication, we are actually going in together to build one telescope that any one of us would find it difficult to afford by ourselves.

Chairman SMITH. So that is mutually beneficial?

Dr. ULVESTAD. Yes, I think that is mutually beneficial, and an example—and we keep coming back to the Atacama Large Millimeter Array, but originally there were concepts for a similar telescope in Japan, in Europe and in the United States, three different telescopes that were all going to end up fairly close to each other in Chile. Rather than building those three separate telescopes, by the three areas of the world coming together, we were able to build one much more capable telescope that we all can use.

Chairman SMITH. Okay. Thank you. Let me ask you all this final question, and that is, what new technology do we need to develop in order to expedite the process of detecting organic life on an exoplanet, and do we need to do more than we are doing? If so, what do we need to do and when do you expect us to have that blockbuster news that there is possible life on another planet? Dr. Doyle?

Dr. DOYLE. Well, of course, as mentioned, you need a much larger telescope, but the detection of oxygen would be definitely an indicator of life on another planet. If it transits, you can also—that is another method for detecting oxygen on an exoplanet.

Chairman SMITH. Do we have the technology now to detect oxygen on another planet?

Dr. DOYLE. If there was a very close star like an M star and a very close orbit and we got lots of transits and we could differentially subtract, we might be able to squeeze by and get an oxygen line or so. But the next mission, of course, is to get the nearby transiting planets, and then we could consider—like Dr. Grunsfeld said, nature is the one that will decide whether we can do that in the near future.

Chairman SMITH. Dr. Grunsfeld, anything more we should be doing to expedite that time?

Dr. GRUNSFELD. A critical limitation is really the ability to separate the light from a bright star from the light from a very dim planet next to it that is in reflected light, and so we are spending a fair amount of technology funds and researchers working on techniques to do that light suppression across a broad variety of fronts, four or five different techniques. So we are making a lot of progress. I think within five years, we will have demonstrated that if we put one of those instruments on a new large telescope, we would be able to detect essentially signs of life if they are as obvious as they are on Earth.

Chairman SMITH. We are going to hold you to that within five years.

Dr. GRUNSFELD. We will have the technology. You can hold me to that.

Chairman SMITH. Okay. Dr. Ulvestad, any more thoughts on that?

Dr. ULVESTAD. I think the key that Dr. Grunsfeld just referred to is really being able to separate the light of a dim planet, which a planet like Earth is dim when it is many light-years away, from the light of the very bright star that is its host. For instance, the instrument I mentioned in our Gemini telescope is one of the steps along the way, but I also mentioned that it could only detect planets that were out farther than Jupiter, which is not where we expect Earth planets to be. We have still got a ways to go to be able to dull the star down to the dimness we require.

Chairman SMITH. Thank you all for your testimony. Thank you, Mr. Chairman.

Chairman PALAZZO. I now recognize Ms. Bonamici for five minutes.

Ms. BONAMICI. Thank you very much, Mr. Chairman and Ranking Member, for this interesting hearing, and thank you to the witnesses for your expertise. I am going to ask two questions together because in the interest of time, hoping that each witness can respond to each. We have also had discussions in this committee about near-Earth objects and the potential for asteroid incidents, and in those hearings we talked a lot about international collaboration because obviously this is not just an issue that affects our country. So will you each discuss briefly the nature of international collaboration in the exoplanet research? The second question has to do with more of a big-picture issue. As Members of this Committee, we are privileged to be frequently presented with this extensive information on these issues and hear from people with expertise, and then when we are back in our districts, we often find that the public at large lacks specific information about the work that NASA is doing, and importantly, how it affects them. So with that in mind, could you also address how you publicize what you are doing, how you educate the public about not only the discovery of exoplanets but how to best translate that into the benefits to the public at large. Thank you. I will ask each of you to respond to those two issues.

Dr. GRUNSFELD. I will go ahead and start. Almost everything we do in NASA has large international collaboration—the International Space Station, the James Webb Space Telescope. These are partnerships where there is integral collaboration between the European Space Agency, the Canadian Space Agency, the United States, in the case of the space station, Russia and Japan, and these are working great. I would say probably 90 percent of everything in the Science Mission Directorate is an international collaboration at some level where we are contributing to leadership of a European instrument or another country is contributing to leadership in one of our programs. The James Webb Space Telescope is an example the United States is leading. Even on the Hubble Space Telescope, originally that was a 15 percent share of the European Space Agency. But when we actually go to use the telescope, it is very broad, and of course, all of our data is public and so anyone can actually use it and so that is much further.

When we discover things, we put them out as press releases, we put them on Web sites, but more importantly, we have an educational public outreach program, where the scientists work with master teachers and that gets into curriculum materials, into the textbooks and into pre-service and in-service teachers who then work with millions of students. That is how we work through the educational side. Through more informal education, we reach out to libraries across the country, planetariums and museums. We do exhibits and shows. All of that contributes to the public knowledge of the science benefits from NASA.

Ms. BONAMICI. Thank you. Dr. Doyle?

Dr. DOYLE. On the Kepler team, I would say we have a huge number of countries represented. There is the Astrobiology Consortium, which is centered in Denmark, but there are 500 members of that, and that is just a spin-off from the main Kepler science team. So I would say Kepler is automatically international.

With regard to reaching out and educational activities, one of the things that we are doing is basically starting a series of a kind of a wiki university where people can learn about life in the universe from the SETI Institute and take classes and so on, and I don't see any reason why they couldn't pass the SAT after taking our classes. So it is free and online, and let us go for it.

Ms. BONAMICI. Thank you. Dr. Ulvestad?

Dr. ULVESTAD. Yes, first on the international front, like NASA, most of our major activities now are international in terms of building big telescopes and operating big telescopes. But I will honestly say that there is also some competition there in the use of those telescopes. We would like the scientists from the United States to actually be leading in the discoveries. So they may be in collaborations, and in fact often are with other international scientists, but we do want to make sure that the U.S. scientists have the opportunities to use the tools we have built.

Now, you mentioned near-Earth objects so I will just pick up on that for a second. The number one ranking in the National Academy Decadal Survey for a ground-based instrument was actually something called the Large Synoptic Survey Telescope, and one of its science goals is to characterize the asteroid population in our own solar system and can do that very extensively including near-Earth asteroids. That happens to be not an international partnership but a partnership with the Department of Energy, so you may consider them international relative to NSF and NASA. They have slightly different cultures than we have. But that is a different sort of incredibly valuable partnership.

With respect to the public information, one of the requirements we have at NSF for everybody who applies for a research grant and for our large facility managers is something called broader impacts. They are required to tell us what they are doing, will do in their grant for broader impacts to the public. So in getting ready for this hearing, I was actually looking at the research grants that we have been making on exoplanets over the last several years, and a large fraction of those people, their broader impacts involved going into high schools. It ranged between K–12 but high schools seem to be a particular point that they were interested in, and that, if I can pick up on a previous question, is very important because——

Ms. BONAMICI. I am sorry. My time is expired. I yield back.

Chairman PALAZZO. Thank you, Dr. Ulvestad. I now recognize Mr. Rohrabacher for a couple minutes, not the full five.

Mr. ROHRABACHER. Let me just note that we have been engaged in a search for intelligent life for a long time over in the Senate, however, and sometimes it is hard to determine.

I just want to make sure we understand that the last mission concept does not necessarily rely on the SLS rocket, does it not? There are other two proposed architectures for this system that would not require us to build this big booster and instead could be launched on EELV-class launch vehicles. Isn't that correct?

Dr. GRUNSFELD. Yes. The Advanced Large Area Space Telescope concept is one of these new-world-type future large telescopes, and in that study there were three telescopes studied: an 8-meter diameter——

Mr. ROHRABACHER. The answer is yes?

Dr. GRUNSFELD. The answer is yes.

Mr. ROHRABACHER. The answer is yes, so this is not—do you know what the budget for the SLS Launch System is?

Dr. GRUNSFELD. I——

Mr. ROHRABACHER. We don't know, so you don't know either. Quite frankly, that was a leading question.

Dr. GRUNSFELD. All right.

Mr. ROHRABACHER. And if that money was going to be taken out of your budget to develop the SLS Launch System rather than go with the launch systems that we have already got, would you be supportive of that?

Dr. GRUNSFELD. No.

Mr. ROHRABACHER. Right. I just want to make sure these are on the record because there is a lot of people pushing for the SLS Launch System and we don't even know what the budget is, we don't know where the money is coming from, and it is really possible if we do that, we will just defund all the things the SLS is supposed to carry, meaning your projects.

The last thing is Arecibo Telescope. I noticed that the NSF Arecibo Telescope Observatory was actually the ones who found the first evidence in this exoplanet. Let me just note, we almost closed that down for lack of funds, and some of us understood just how important that was. Let us make sure we—because that telescope really remains a very important part of the very projects that we are talking about. So, Mr. Chairman, thank you very much for the hearing and I just want to make sure we got on the record. Thank you.

Chairman PALAZZO. I want to thank the witnesses for their valuable testimony and the Members for their questions. The Members of the Committee may have additional questions for you, and we will ask that you respond to those in writing. The record will remain open for two weeks for additional comments and written questions from Members.

The witnesses are excused and this hearing is adjourned.

[Whereupon, at 11:00 a.m., the Subcommittees were adjourned.]

Appendix I

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Laurance Doyle

Carl Sagan Center for the Study of Life in the Universe

SETI INSTITUTE

June 26, 2013

Reply to Additional Questions From the Chairman of the Subcommittee on Space and the Chairman of the Subcommittee on Research and the Ranking Member of the Committee on Space, Science and Technology of the U.S. House of Representatives, Congress of the United States of America Related to the the Session on May 9, 2013 on the Topic of "Exoplanet Discoveries: Have We Found Other Earths?"

Dr. Laurance R. Doyle – SETI Institute

Please Note: Answers are from the perspective of a scientist in the field rather than management within NASA or NSF. The responder addresses as many questions as he could contribute helpful information about but respectfully declined to answer questions in which he was not knowledgable or could only contribute very limited information regarding.

Questions from Representative Palazzo

Q1) How can the government better leverage non-government organizations like yours to increase our efforts to search for exoplanets?

A1) In the case of SETI Institute we are entirely dependent on funding from grants and donations. The SETI Institute has more than a dozen scientists on the Kepler Science Team, Co-Investigators on Mars missions like Spirit and Opportunity, and astrobiologists investigating extremes of biology in dozens of countries throughout the world. Such smaller scientific research organizations can often drive the state-of-the-art science where larger organizations must support more mainstream work. Continued support for such programs, and specifically in the field of extrasolar planets, will remain essential for such scientific breakthroughs.

Q2) What work have private organizations conducted on education and public outreach initiatives related to exoplanet discoveries?

A2) In the case of the SETI Institute, we have managed the NASA Kepler Mission Educational outreach, the SOPHIA aircraft educational outreach, and written educational materials—specifically on the detection of exoplanets—for grade schools and high schools, and taught extrasolar planets classes at the university level. As one example, the author wrote the first chapter on extrasolar planet detection methods for a graduate-level textbook published by Cambridge University Press. As for public outreach, the SETI Institute receives about one million visitors to our web site each month, where the public can inform themselves about exoplanets—including simulations of planetary transits and animations about the Kepler spacecraft.

Q3) What new capabilities does the Atacama Large Milimeter/Submilimeter Array (ALMA) provide that were not previously available? What research goals do we hope to fulfill using this tool?

A3) The ALMA array can provide answers to questions of planetary formation processes that could not be answered by optical or infrared telescopes because of obscuring dust. An example of the use of ALMA is in an issue of *Science* for this month. In this paper Marel et al. (2013, vol. **340**, pp. 1199-1202) have observed a region of enhanced small protoplanetary particles that are trapped in rings—in other words, the beginnings of the accretion of planets. This is just one current example of the fact that various astronomical instruments observing at a variety of wavelengths are not just important but necessary in order to understand the whole process of planetary system formation from interstellar dust to a mature solar system.

Q4) What have we learned about the exoplanets from the Hubble telescope? What have we learned by using the Spitzer Space Telescope?

A4) It would take volumes to list the contributions to the discovery and understanding of extrasolar planets from the Hubble Space telescope (HST) and the Spitzer telescope, so perhaps some examples can best be stated. HST has, for example, studied the atmospheres of selected exoplanets, detecting atmospheric constituents for the first time. It has discovered planet-forming regions in our galaxy, actually imaging the forming solar systems' protoplanetary discs. It has discovered the farthest known exoplanets, implying that planet formation is not just a process that happens in our own region of the galaxy.

The Spitzer telescope was designed to observe at longer wavelengths than the HST and was able to detect direct light from exoplanets. (The Kepler telescope, for example, detects the shadow of the planet as it moves across the disc of the star.) The Spitzer telescope has made it possible to detect atmospheric temperatures, winds, and constituent elements of selected extrasolar planets. Spitzer's ability to observe in the far infrared has allowed it to peer into young solar systems and study the planet formation process in detail—how and where planets and asteroids form. Spitzer has been an invaluable aid to the Kepler Mission as well, in obtaining information about the parent stars around which planets have formed. A part of the original Kepler Mission was to characterize the stars—number and type—around which planets form, and "warm" Spitzer has been an excellent instrument in support of this mission goal.

Q5) How will the James Webb Space Telescope (JWST) be used differently than either of the Spitzer or Hubble telescopes with regard to exoplanet observation and discovery?

A5) Two of the four goals of the JWST are to learn more about "The Birth of Stars and Protoplanetary Systems" and "Planetary Systems and the Origin of Life." For the first of these, the JWST is optimized for observing in the infrared and has a large enough aperture to actually observe details of star- and planet-forming processes deep within condensing interstellar clouds (i.e., deep within the "cocoon" of young stars that planets are forming around). By being able to watch the details of planetary system formation JWST can answer such questions as, "Do planets form where they are later observed or do they migrate inward as some models imply?" This has important implications for the abundance of Earth-like planets as giant planets migrating inward may be expected to remove potentially habitable planets from such a solar system. Now that the Kepler telescope has determined the frequency of exoplanets—the distribution of their sizes, for example – JWST can provide the unique capability of obtaining spectra of those exoplanets as they transit across the discs of their parent stars, allowing exoplanet scientists to start comparing the chemical compositions of many exoplanets with each other and with our own Solar System.

Q6) The Space Telescope Science Institute indicated that a key technology for determining exoplanet habitability is the development of a high performance coronagraph to block a star's brightness so that measurements can be taken with a spectrograph to analyze the atmospheres and surfaces of exoplanets close to a star. How complicated is this endeavor? What would such a mission cost?

A6) The brightness of the Sun is about a billion times the brightness of the reflected light from Jupiter, our largest planet (at optical wavelengths). But if one can block out the light of the star effectively, then one may be able to image the planet, take spectra of its atmosphere, and study its characteristics directly. Such a coronagraph (there are several designs—for example, a vortex coronagraph uses nulling interference to cancel the star's light) will be an essential tool for obtaining the spectra of extrasolar planets. The ultimate goal from a life-in-the-universe standpoint will be the development of coronagraphic technology that can obtain spectra of terrestrial planets within the habitable zones of their parent stars to determine if there are atmospheric constituents indicative of exobiology. The development of coronagraphic technology—including nulling interferometry—is very complicated as one is trying to block the light from the much brighter star in order to see the tiny reflected light from the planet. It has been likened to viewing a firefly on the rim of a searchlight. I do not have access to the budget for such systems but I think getting the spectra of nearby habitable planets is the most important next step in the discovery of life in the universe.

Q7) The Space Telescope Science Institute indicated that JWST could be optimized for exoplanet research by using a starshade. How complicated is this endeavor? What would such a mission cost?

A7) The starshade concept proposes to use a sunflower-shaped star occulter flying about 80,000 miles in front of an orbiting telescope—JWST, for example. The design must not simply directly block the starlight—so that planets can be detected and isolated spectroscopically—but also be able to deflect diffracted starlight from getting around the occulter, as well. The starshade occulter would be tens of meters in diameter and, as proposed, be able to unfold in orbit. One important complication is moving the shade around so that different star systems could be observed; this could be one of the big expenses. Currently, I believe, the system has been estimated to cost around $3 billion.

Q8) Are there other factors, such as the eclipsing binary star systems, that need to be accounted for to ensure that exoplanets are correctly identified?

A8) On the assumption that the question refers to the detection of exoplanets by the transit method, where the planet moves in front of the star and the shadow of the planet is detected, there are a number of checks one must do in order to confirm a planet. In addition to many instrumental corrections (several electronic effects can produce reductions in brightness with time in the light curve that resemble planetary transits) and the presence of eclipsing binary systems in the background, heavily spotted stars can have brightness variations that might be mistaken for planetary transits. (Starspots are magnetic field twists on stars similar to sunspots on our Sun.)This can be checked by determining the rotation period of the star as well as its starspot activity (which is done through spectroscopic observations of the singly ionized calcium H&K lines, for example). While background eclipsing binary systems are the most abundant source of "false positives," another important consideration for the detection of Earth-like planets would be the separation of a background star with a giant planet producing a signal identical to that of a foreground star with an Earth-sized planetary transit. The best option for ruling out this type of false positive is the transit timing method, which can be used if other planets exist in the same star systems where an Earth-like planet is suspected. The planets of a given system will produce a gravitational tug on each other, thus varying the time that each planet transits that star. This transit timing variation (TTV) is the best way to insure that the event one is observing is actually within the foreground star system since the other planets in that system are feeling its gravitational pull. For circumbinary planets one looks for the changes in the timing of the stellar eclipses and this is called an eclipse timing variation or ETV.

Q9) The National Academies' 2010 decadal survey recommended the improvement of the precision radial velocity method. How has this method improved since the report was issued? What are the steps that need to be taken for further improvement?

A9) The radial velocity method detects a minute shift in the spectral lines of a star as it is offset by a planetary mass. For example, Jupiter produces a 12.4 meter per second shift in the Sun's position every 11.86 years, while the Earth produces only a yearly 0.1 meter per second shift in the Sun. Thus the radial velocity method cannot, at present, detect Earth-mass planets. The reason that the transit method can detect Earth-sized planets is that, in this method, one is comparing the *area* of the planet to the area of the star (as the planet transits the star). In the radial velocity method, one is comparing the mass of the planet to the mass of the star, which is essentially a *volume* comparison. For example, if we use Jupiter and the Sun as a comparison—

they are about the same density, and Jupiter has about 1/10th the diameter of the Sun—then Jupiter causes a 1/10th x 1/10th = 1% drop in brightness during a transit, but offsets (Doppler shifts) the Sun by 1/10th x 1/10th x 1/10th = 0.01%. The current precision of the radial velocity method is 0.3 meter per second, which would allow the detection of Earth-mass planets around stars one-third the mass of the Sun (M-spectral-type red dwarf stars). The European EXPRESSO consortium, however, projects that 0.1 meter per second may be reached by improvements in fiber optics, radial velocity standards, and adaptive optics. Kepler has shown that all stars are variable stars at this level, so much will be learned about stars at a much more intimate level with these new instruments. Isolating the signal of Earth-mass planets from this new level of stellar micro-variability will be a necessity.

Q10) The National Academies' 2010 decadal survey noted that the period from 2010-2015 would see the completion of ground based mid-infrared interferometric instrumentation designed to study the dusty disks surrounding stars. What is the status of the development of these instruments? What improvements still need to be made? How has their development furthered our study of exoplanets?

A10) Ground-based infrared telescopes with apertures of 2.5-meters or more are VISTA (4.1-meter in Chile), UKIRT (3.8-meter), Herschel (3.5-meter in orbit, operative until April 2013), IRTF (3-meter in Hawaii), and SOFIA (a 2.5-meter in a 747 jet). I am not up-to-date on the status of various instruments for these telescopes, but I can comment on the importance of mid- and far-infrared observations of dusty discs (i.e., protoplanetary discs) around stars to the understanding of the fundamental processes of planetary system formation. Shortly after low-mass stars are born, almost all of them have rotating discs of dust and gas around them from tens to hundreds of astronomical units (AU = 93 million miles). These protoplanetary discs can survive for several million years during which time photoevaporation and dust ejection can occur along with regions condensing into centimeter-sized bodies which can then accrete into larger, planetesimal-sized bodies. Observations in the infrared (and millimeter) wavelengths can determine the status of this planet formation process at different ages, and measure the mass, size, structure, and composition of the preplanetary processes involved. Thus, knowing how planets form is an essential element in understanding extrasolar planets.

Q11) The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that between 2008 and 2013 preparations begin for a "space-borne astrometric mission capable of surveying between 60 and 100 nearby main sequence stars with the goal of finding planets down to the mass of Earth orbiting their parent star within the habitable zone." What progress was made towards achieving this goal? Are there limiting factors beyond budget constraints? What is the status of these preparations? What is the expected timeline of such a mission?

A11) The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force proposed to "fast track" the detection of potentially habitable planets by looking for astrometric displacement of very-small-mass M-dwarf stars in the solar neighborhood. Since M-dwarf stars constitute about 75% of all stars in the galaxy, there are sufficient target stars of this type nearby. However, planets in the habitable zone of M-dwarf stars are generally going to be tidally locked in synchronous rotation (i.e., one side of the planet always faces the star). This is because these stars are about 1/100th the brightness of the Sun, so one has to get about ten times closer to be in the habitable zone. But at the same time, the tidal forces increase by a factor of 1000. For many years it was believed that such star systems would not support habitable planets, but detailed atmospheric models have shown that such habitable planets could exist around M-dwarfs (see [1] Haberle, McKay, Tyler, and Reynolds, 1996, "Can Synchronously Rotating Planets Support an Atmosphere?" in L. R. Doyle (ed), *Circumstellar Habitable Zones: Proceedings of the First International Conference*, Travis House Publications, Menlo Park, CA; and [2] Heath, Doyle, Josh,i and Haberle, 1999, "Habitability of Planets Around Red-Dwarf Stars," *Origins of Life and Evolution of the Biosphere* **29:** 405–424). Using the criteria that persistent liquid water defines a habitable planet, such red-dwarf-star planets qualify, but weather and hydrological processes would be quite different from those of Earth (for example, such planets would have a *equatorial* ice cap on the dark side). The biggest recent step toward this goal has been taken by the funding of the TESS mission, which is to perform a transit survey, similar to Kepler, but with the purpose of detecting mostly nearby M-dwarf transiting planets. This will give an idea of the planet population of nearby M-dwarfs that could inform the astrometric mission proposed.

Q12) The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that between 2008 and 2013 scientists engage in the technological development of "space-borne direct detection capabilities to find and characterize Earth-sized planets." Specifically, the recommendation notes the need for the development of advanced wavefront sensing and control, next-generation deformable mirrors, low-noise detectors, coronagraphic masks, ultraprecise optical surfaces, and validated diffraction modeling. Please describe the progress of these technological developments. Which have been achieved to the satisfactory level to operationalize for use in exoplanet discovery? Which still require work? Are there additional specific capabilities that are needed?

A12) All these fields have vastly improved over the past decade and will be needed for the imaging detection and characterization of Earth-like planets. A specific goal, for example, would be the detection of the 9.6-micron spectral line in the atmosphere of an extrasolar planet. Since free oxygen is out of equilibrium with constituents of an atmosphere (since oxygen is so highly reactive it should not exist by itself for long in an atmosphere) such a detection would be highly indicative of ongoing production of oxygen on that planet—in other words, photosynthesis. The progress toward achieving this goal with each improvement would require a larger report than this, but much work is required in each of these fields in order to determine if a potentially habitable planet is indeed, actually inhabited (by forests, which I think, would be the first determination). It would be appropriate for a NASA task force to provide an update on these developments.

Q13) The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended a census of exo-zodi systems around solar type stars. Did such a census take place? If so, what were the results? If not, what progress was made towards achieving this goal?

A13) The detection of extrasolar zodiacal light would be indicative of material present in that system for the formation of planets, and inform direct imaging efforts. Zodiacal light is the dominant source of brightness in our Solar System within the wavelength range 5-50 microns (thermal emission). The 1-100 micron-sized particles that constitute the zodiacal dust are expected to form near the habitable zone of a star, and are also a major source of interference in the detection of extrasolar planets in this wavelength range. This author is not aware of any census of extrasolar zodiacal clouds within the last several years.

Q14) The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended searching the nearest thousand M-dwarfs for transiting low-mass exoplanets with radial velocity measured masses. What progress was made toward achieving this goal? Are there limiting factors beyond budget constraints?

A14) There has been significant progress in achieving the goal of searching the nearest M-dwarf systems for transits in the selection of the TESS (Transiting Exoplanet Survey Satellite) mission for flight within the next few years. TESS is predicted to discover between 1,000 and 10,000 planets around the brightest stars in the solar neighborhood and some of these will be nearby M-dwarfs. The most limiting factor is that M-dwarf systems are intrinsically faint. Typically they have an absolute magnitude of 10 to 15 or about 10,000 to one million times fainter than the Sun. Although solar-type stars are the main target for TESS, it should discover about 1,000 M-dwarf transiting planets.

Q15) The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that emphasis be placed on the development of near-IR spectrographs with one meter per second precision for radial velocity planet surveys of late M-dwarfs once feasibility at 10 meters per second has been demonstrated. What is the status of this recommendation?

A15) Precision radial velocity measurements depend upon a comparison cell using a gas with well-known spectral lines. Part of the progress in extending this methodology to the infrared includes recent improvements in the specification of spectral lines in this region. Ten meters per second precision should certainly be achievable but this author is not up-to-date on specific recent developments in this field.

Q16) The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that operation of the Spitzer telescope continue as a "warm observatory" for characterizing low-mass transiting planets around main sequence stars. Is this recommendaton feasible? If so, is NASA using Spitzer for this purpose?

A16) NASA is using Spitzer to help to characterize transiting planets (this was a specific proposal funded through the Participating Scientist Program—David Charboneau of Harvard University was the selected participant).

Q17) The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended adding a single two meter telescope to increase the efficiency of a ground-based microlensing network. Has this taken place? If so, has this addition increased the efficiency of ground-based microlensing? If not, is there a time frame for adding the 2-meter telescope? What progress was made toward achieving this goal? Are there limiting factors beyond budget constraints?

A17) I am not aware of a new 2-meter telescope dedicated to microlensing, but 2-meter telescopes are fairly common. The Advisory Committee was not specific as to where they intended this telescope to be constructed, so more information would be needed to ascertain if they have built this telescope. Microlensing is very sensitive and can detect also Earth-mass planets, but in general, follow-up studies are difficult unless the planet also transits its star.

Q18) The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that ground-based capabilities such as extreme adaptive optics (AO, a technology to reduce wavefront distortions) be implemented in the lab and on eight meter class telescopes. Has extreme AO been implemented according to these recommendations? What progress was made towards achieving this goal? Are there limiting factors beyond budget constraints?

A18) Assuming that extreme AO refers to improvements in reducing wavefront distortions, this technique is being implemented at a number of facilities and at the Keck and Gemini telescopes (as well as the European Very Large Telescope array of four 8-meter telescopes). While spatial AO has been very successful it is more difficult to achieve photometric AO because light is refracted by the atmosphere out of the telescope aperture. In other words, for photometric precision like that of Kepler, telescopes will likely still have to be in space.

Q19) The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended continued support for archival analysis of Spitzer, Chandra, Hubble, and ground-based data. What is the status of archival analysis of these data? Are there limiting factors beyond budget constraints?

A19) There are NASA programs to encourage the use of spacecraft archival data and, as far as I know, these are well supported. These spacecraft (as well as now Kepler) are rich data treasures where new discoveries can be made. The data thus preserved may be useful even a half-century or more from now.

Q20) The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended moving planetary system architecture studies and multiple-planet statistics beyond the 3 to 5 Astronomical Unit "ice-line" boundary for G-type stars by continuing long-time baseline Doppler spectroscopic studies in the next five years. Do you anticipate that this will be possible? What progress was made towards achieving this goal? Are there limiting factors beyond budget constraints?

A20) It is certainly an achievable goal to move beyond 5 AUs with Doppler spectroscopic studies—this requires measurements below about 13 meters per second, which has already been achieved. If jovian-mass planets are responsible for the deflection of comets in our Solar System—and thus are required for a "shield" for habitable inner planets, then the frequency of such outer giant planets would be an important factor in determining the habitability of an Earth-sized planet in such a system. Progress is being made along these lines by ongoing Doppler projects, including the completion of a new 2-meter telescope at Lick Observatory for this purpose.

Q21) The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended launching a Discovery-class space-based microlensing mission to determine statistics of planetary mass and the separation of planets from their host stars as a function of stellar type and location in the galaxy. Do you think such a mission is possible? What barriers might there be to achieving this goal? Would there be alternative means of obtaining the same statistics?

A21) Such a mission is certainly possible. Microlensing can provide planetary statistics down to at least Earth-mass planets. The NASA Kepler mission has provided some of the same statistics but microlensing will likely require that many more stars to be observed.

Q22) The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that the next five years see the construction of a 30 meter telescope to do optical direct detection of giant planets. Do you think construction of wuch a telescope is likely to take place in the next five years? Would this be an ideal project for international collaboration? Why or why not?

A22) I would like to think that construction of a 30-meter-class telescope would be well on the way to (as astronomers call the opening of a telescope) "first light." Yes, it is certainly a very good opportunity for international collaboration, which already universally takes place in the professional astronomical community.

Q23) The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that the next five years see the impllementation of next-generation high spatial resolution imaging techniques on ground-based telescopes. Do you think implementing such techniques is feasible? Are there limiting factors beyond budget constraints?

A23) Yes, such implementation is possible, and adaptation of many of the ground-based telescopes with AO could certainly increase their utilization.

Questions from Representative Bucshon

Q1) 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?

A1) Governmentally funded exoplanet research (such as the Kepler mission) is generally on a scale of support far above the private sector (selected ground-based telescopes usually in the 2-meter class or smaller). Planet discoveries themselves, however – when refereed and validated—are treated in the scientific community on an equal basis. It is for breakthroughs like the discovery of Earth-sized planets around Sun-like stars that space-based telescopes are required, and that level of funding has not usually been available from the private sector. But yes, I have found that all legitimate exoplanet discoveries are weighed in the scientific community according to the importance of the scientific breakthrough itself.

Q2) What is the single most important technological advancement that is needed to further exoplanet research? What advancement should be our highest priority?

A2) In a book written in 1870 by Dr. Proctor on astronomy (The Plurality of Worlds) he states that astronomy is of most interest to the public when the subject of the habitability of other worlds is discussed. I think this has not changed. The Kepler mission, for example – with the mission goal of detecting Earth-sized planets within the habitable zones of their stars—has caught the imagination of the public because such a discovery would be one step closer to finding life in the universe. With this in mind, I would say that the next big goal would be to detect signs of exobiology in the atmospheres of planets in their habitable zones. For this the technology of flying an array of telescopes (similar to the Terrestrial Planet Finder concept) would be a priority. There are many intermediate steps that would need to be taken to achieve such a detection, but in my opinion the detection of biomarkers in an extrasolar planetary atmosphere would be a main priority and unifying goal for exoplanet research that the public could also understand and identify with.

Q3) What techniques are used for planet detection and characterization? How do you hope to specifically refine existing techniques going forward? What potential do these techniques have that has not yet been realized, or that you think will be better realized in the coming years? Are there any techniques that can be performed by amateur astronomers?

A3) I have written a chapter on extrasolar planet detection techniques: (L.R. Doyle, 2008, "Overview of Extrasolar Planet Detection Methods and Nearby Targets for Exobiological Searches," in *Extrasolar Planets*, H.-J. Deeg and J.A. Belmonte (eds), Cambridge University Press, Cambridge, UK, pp. 1-23). The main methods include (1) Timing of pulsars—the pulses can be timed and if the pulsing star is being offset by a planet this can be detected; (2) Radial velocity variations—the spectral lines from the star move back and forth as the star is offset by a planet toward to away from the observer; (3) Gravitational microlensing—a planet moves in front of a star so precisely that the slight bending of spacetime around the planet causes a focus of the starlight for a few minutes to about a day; (4) Astrometry—this technique measures the wobble of a star due to a planet going around it and offsetting it about their common gravitational fulcrum (called the "barycenter"); (5) Imaging—if one can block the light of the star, one can get an image of the planet; (6) Radio flux—some planets, especially jovian-type planets, have strong magnetic fields and can emit significant radio flux—this will require a very large radio telescope, however (like the Square Kilometer Array being built in Australia and South Africa); (7) Transit photometry—this method relies on the planet having an orbit that crosses the stellar disc, in which case the shadow of the planet is detected (this is the method the Kepler telescope uses); (8) Phase reflection variations—this method relies on the changing phases of the planet as it orbits its star, somewhat like the changing phases of the moon as it orbits the Earth; and (9) Eclipsing binary timing—this method, for finding circumbinary planets, uses the timing of the central two stars as they eclipse each other. Periodic changes in the eclipse times indicate a circumbinary planet is offsetting the binary system about the planet/binary barycenter.

Many of these methods can be performed by amateur astronomers but perhaps the most accessible is the transit method. Planets have been discovered with even very small telescopes, and amateur CCD cameras are almost as good as professional CCD cameras for many uses. Also, I would estimate that there are at least a few more detection techniques that will emerge as sensitivity increases in each of these techniques.

Q4) What have we learned about planet formation from studying exoplanets?

A4) We have discovered that our own Solar System is not typical and that just about any configuration of planets can form (and have). So actually the new rule is that there do not seem to be any rules, or limitations, on what nature can make as far as planetary systems go. We've really seen the birth of a new field of exploration these past two decades, a field that will still be full of new discoveries for centuries to come.

Questions from Representative Edwards

Q1) Subsequent to the hearing, Kepler went into safe mode due to loss of attitude control. If the spacecraft can be operated in a degraded mode, would you argue for extending the mission for another two years of operations, and if so, why? What scientific objectives could be pursued in a degraded mode?

A1) A decision to extend the mission would, of course, rely upon what we can determine the precision of the degraded mode to be (still to be determined). The detection of Earth-sized planets is still possible even with degraded photometry if there are a sufficient number of additional transits and the photometric precision is still fairly good. Kepler can measure stellar brightness about 100 times better than it has ever been measured before, and even a degraded Kepler is significantly better than any previous telescopes for measuring brightness changes in stars. An extended mission would also allow longer timelines for detection of circumbinary planets (my field) because the more stellar eclipses that can be obtained, the more precision is obtained for the detection of non-transiting circumbinary planets, even down to terrestrial masses in some cases. In addition, the known planetary systems would have more transits and the timing changes of these (called TTVs for transit timing variations) would be needed to detect any Earth-mass planets that are "hiding" in these systems (i.e., that don't transit the star but nevertheless show their presence by pulling on the transiting planets and changing the times they transit). So I would argue for the extended mission because so much more could be discovered and it is still the best photometric telescope we have.

Q2) With the pace of exoplanet discoveries accelerating, and the nature of exoplanet characterization evolving, is the current way in which exoplanet data is formatted and catalogued adequate to handle future discoveries and adequate to enable the broadest access by the research community? Are any changes needed in order to facilitate the use of these data?

A2) The present system for accessing most of the data is certainly adequate but requires fairly specialized tools to access—that is amatuers would have to be fairly advanced to work with the data themselves. I think there is great potential for truly user-friendly tool development so that students could look at, for example, Kepler light curves and easily learn to recognize different kinds of stars, etc. (I utilize a Python script to display such light curves myself). So I would say the data folks are doing a great job, but, as an educational component, data could always be made more user-friendly.

Q3) How does the study of exoplanets relate to other areas of space science research, including astrobiology? Is the research portfolio at NASA and NSF flexible and broad enough to respond dynamically to any dramatic findings of Earth-like signatures?

A3) The goal of the Kepler mission is a good example of exoplanet research overlapping with astrobiological research. Finding Earth-sized planets within the habitable zone of their stars would give places outside the Solar System for exobiology. It would immediately extend astrobiology beyond our own planetary system and give an indication of how prevalent life could be. If Earth-like signatures were discovered I do think that both NASA and NSF could respond very quickly to focus on this discovery as they have in the past for events such as the impact of Comet Shoemaker-Levi into Jupiter. Kepler's search for habitable planets requires knowing where the habitable zones of different types of stars are located. This requires a look at studies in astrobiology because the habitable zone for bacteria is much broader than the habitable zone for humans, for example.

Q4) Should the information being disseminated on discoveries of Earth-sized planets be enhanced so that the public recognizes the challenges of identifying the existence of Earth-like conditions on these planets? How can the public's interest be engaged on a sustained basis in an environment where repetitive "discovery" announcements could lead to diminished interest? If the discovery of Earth-like planets is likely the only item of interest to the public, what can be done to address such expectations? How are budget reductions to NASA's education and publish outreach (EPO) activities affecting the ability to engage the public on exoplanet discoveries?

A4) Yes. With additional details about these discoveries I think the public would actually become more interested in, and also more realistic about, exoplanet discoveries. I think there are visualization tools that could be utilized to a great extent to "fly" people around the Kepler field, for example, where they could explore each new planet and get information on them and how they compare with our own Solar System planets. Each new discovery could be a new Kepler "app" upgrade, as one idea. I do think there is a large contingent of society that does not look at missions like Kepler as just news stories but as ongoing progress in humankind's awareness of its place in the universe. Radio SETI has not succeeded yet, but we still get about one million visits per month at the SETI Institute web site. So a large part of the public is interested in topics having to do with life in the universe, and the Kepler mission is making a giant step in narrowing down the frequency of Earthlike planets.

Regarding the EPO programs, we were sorry to see that these activities were not funded. I feel that such educational activities are not just a duty to the public, to show them how their money has been spent well on exploring the universe (and, of course, inviting them to join in) but it is also a key investment in the future. All children naturally love to discover things—they are natural scientists asking "why" all the time—and a little encouragement via these educational programs can go a long way towards encouraging them to explore their universe.

Q5) Beyond its scientific value, does exoplanet research have any broader societal benefits? If so, what are they?

A5) The solution to all problems is, of course, ideas. Sooner or later someone actually has to think to solve a problem. Exoplanets (and astronomy in general) are all about perspective. Finding another Earth-like planet is actually finding ourselves in context, and I think it has the effect of putting things in perspective. Such topics get people seing the bigger picture. When I give talks at schools and ask the students if they'd like to discover other worlds, I am always greeted with the greatest enthusiasm. They like to think about these things. So I would have to say that the broader societal benefits of exoplanet research would be a society, hopefully, with a better perspective on ourselves in the universe, as well as higher scientific literacy and reasoning ability. Here, again, education is a key component of the success of any discovery mission.

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Responses by Dr. John M. Grunsfeld

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEES ON SPACE AND RESEARCH

"Exoplanet Discoveries: Have We Found Other Earths?"

Questions for the Record, Dr. John Grunsfeld, Associate Administrator, Science Mission Directorate, National Aeronautics and Space Administration

Questions submitted by Rep. Steven Palazzo, Chairman, Subcommittee on Space

1. How will the proposed asteroid mission impact exoplanet surveys and characterizations?

NASA refers to the overall efforts to identify, remotely study, redirect and study with astronauts as the "asteroid initiative." The part of the strategy to redirect an asteroid into a stable orbit near the moon and then send astronauts aboard an Orion spacecraft to study it and bring back samples is commonly referred to as NASA's "Asteroid Redirect Mission (ARM)."

President Obama announced in April 2010 a mission to send humans to an asteroid by 2025. NASA's fiscal year 2014 budget proposes a strategy to leverage human and robotic activities for this first-ever human mission to an asteroid, while also accelerating efforts to improve detection and characterization of asteroids.

Our asteroid strategy will help us protect our planet, advance exploration capabilities and technologies for human spaceflight, and help us better utilize our space resources.

The proposed asteroid mission is unrelated to, and will have no direct impact on, exoplanet surveys and characterizations.

2. How do NSF, NASA, and other entities coordinate research amongst themselves?

NASA and NSF both contribute to the search for exoplanets. NASA provides space-based telescopes to identify and characterize potential planets, while NSF builds ground-based telescopes and instrumentation. Both agencies fund research that assists in categorizing and characterizing candidate planets.

NASA and NSF have regular discussions to coordinate research amongst themselves. The NSF Director of the Astronomical Sciences Division and the NASA Director of the Astrophysics Division communicate frequently on common areas of research. The program officers at the two agencies regularly exchange information about submitted proposals to avoid duplication in funding exoplanet and other research by the Federal government. In April 2013, a joint staff meeting was held to facilitate communication and coordination at all levels and in all areas of astronomical research between NASA and NSF.

NASA and NSF respond to joint advisory groups, such as the Congressionally-chartered Astronomy and Astrophysics Advisory Committee (AAAC), which also advise DOE and OSTP, and the National Research Council's Committee on Astronomy and Astrophysics (CAA); these joint advisory committees provide coordinated advice on agency policies and plans.

3. How does the current budget situation impact Senior Reviews that determine what telescopes and spacecraft should be decommissioned in favor of new investments and capabilities?

NASA is building and operating a balanced portfolio of ground-breaking science missions that will reach farther into deep space and reveal previously unknown aspects of our universe. In an era of fiscal responsibility and budget realism, the balance between operating missions and missions in development is very important. Hence, both operating missions and missions in development are operating at lower budget levels to maintain strategic balance.

4. What have we learned about the exoplanets from the Hubble telescope? What have we learned by using the Spitzer Space Telescope?

Although neither was designed with exoplanets in mind, both the Hubble Space Telescope and the Spitzer Space Telescope are being used regularly to detect and characterize exoplanets. Hubble's excellent imaging capability can be used to directly image an exoplanet if it is sufficiently far outside the glare of the parent star. Both Hubble and Spitzer can characterize exoplanets by measuring the differences in light detected when the exoplanet either is or is not blocking light from the star. Together Hubble and Spitzer have provided the majority to date of the measurements of exoplanet atmospheres.

Some examples of Hubble's discoveries include:

- NASA's Hubble Space Telescope was used by researchers to image a debris disk encircling the nearby star Fomalhaut and a planet circling it. The planet, called Fomalhaut b, ranges from 5 billion to 27 billion miles away from the star (for comparison, Pluto ranges between 3 billion and 5 billion miles from the Sun). Astronomers are surprised to find that the debris belt is wider than previously known, and the planet's wide-ranging orbit may provide forensic evidence of a titanic planetary disruption in the system.
- Observations by NASA's Hubble Space Telescope have come up with a new class of planet, a water world enshrouded by a thick, steamy atmosphere. It's smaller than Uranus but larger than Earth. Hubble was used to study GJ1214b when it crossed in front of its host star. During such a transit, the star's light is filtered through the planet's atmosphere, giving clues to the mix of gases. Astronomers found the spectrum of GJ1214b to be featureless over a wide range of wavelengths, or colors. The atmospheric model most consistent with the Hubble data is a dense atmosphere of water vapor.

- NASA's Hubble Space Telescope made the first detection ever of an organic molecule in the atmosphere of a Jupiter-sized planet orbiting another star. The molecule found by Hubble in the atmosphere of the exoplanet HD 189733b is methane, which under the right circumstances can play a key role in prebiotic chemistry — the chemical reactions considered necessary to form life as we know it. Carbon dioxide was also discovered in the atmosphere of this exoplanet.
- An international team of astronomers using data from the NASA's Hubble Space Telescope detected significant changes in the atmosphere of an exoplanet consistent with gases escaping from the planet. The evaporation of exoplanet HD 189733b's atmosphere occurred in response to a powerful eruption on the planet's host star, an event observed by NASA's Swift satellite.

Some examples of Spitzer's discoveries include:

- Scientists used NASA's Spitzer Space Telescope to measure the infrared light from a Hot Jupiter exoplanet and used that to make a temperature map of the planet's atmosphere and determine that the planet is whipped by ferocious winds.
- NASA's Spitzer Space Telescope was used to detect a planet two-thirds the size of Earth in 2012. The exoplanet candidate, called UCF-1.01, is located 33 light-years away, making it the nearest known world to our solar system that is smaller than Earth.

5. How will the James Webb Space Telescope be used differently than either of the Spitzer or Hubble telescopes with regard to exoplanet observation and discovery?

Building on the pioneering observations of Hubble and Spitzer Space Telescopes, the James Webb Space Telescope (JWST) will use transit spectroscopy to determine atmospheric and physical properties of planets ranging in size from Jupiters to Super Earths.

JWST will use direct imaging to find and study young (i.e., still warm) Jupiters and Saturns as well as rings of dust, and icy/rocky planetessimals (asteroid and Kuiper Belts) located far from the parent star in many exoplanet systems.

JWST will have several capabilities that will enable the study and characterization of exoplanets beyond those available with Hubble or Spitzer. For exoplanets that transit bright stars, the Near-InfraRed Imager and Slitless Spectrograph (NIRISS) will enable JWST to characterize the atmospheres, possibly even detecting the signature of liquid water on rocky planets. For more distant transiting planets, the capabilities of JWST's Near Infrared Camera (NIRCam), Near InfraRed Spectrograph (NIRSpec) and Mid-Infrared Instrument (MIRI) will enable imaging and spectroscopic detection of both primary and secondary eclipses, measuring both atmospheric constituents and thermal emission from a wide variety of planets. JWST also has coronagraphic capability in NIRCam and MIRI and a never-before flown capability called non-redundant masking that provides a unique method of exoplanet discovery. JWST's imaging capability is excellent; JWST might – or might not – be able to use direct imaging and spectroscopic observations to study rocky planets around nearby stars. In summary, JWST's capabilities are broader, stronger, and more comprehensive than Spitzer and Hubble Telescopes due to JWST's expansive and innovative technologies to observe and discover potentially new exoplanets.

6. **The National Academies' decadal survey stated that in order to answer the most pressing questions about exoplanets, scientists will ultimately require a dedicated space mission. However, that same decadal survey went on to state that "it is too early to determine what the design of that space mission should be, or even which planet-detection techniques should be employed. It is not even clear whether searches are best carried out at infrared, optical, or even ultraviolet wavelengths." On April 5, 2013, NASA selected the Transiting Exoplanet Survey Satellite (TESS) mission for launch in 2017.**

   a. **Why did NASA select a space mission to study exoplanets when the National Academies' decadal survey indicated that it was too early to determine the most optimal design or technique?**

      The cited recommendation of the 2010 "New Worlds, New Horizons" decadal survey refers specifically to the design of a future "New Worlds Mission," a mission capable of conducting direct imaging and spectroscopy of Earth-sized rocky planets in the habitable zone of stars in the Solar neighborhood. Before we can conduct such a mission with a New Worlds Mission, it is necessary to discover which nearby stars have rocky planets in the habitable zone; that is the science objective of the Transiting Exoplanet Survey Satellite (TESS) mission. TESS will make an important contribution to an eventual New Worlds Mission by providing an all-sky survey of planetary systems in our neighborhood of the galaxy, all of which will represent potential targets for a future New Worlds Mission. In this regard, TESS advances one of the key science objectives for the current decade set forth in the 2010 decadal survey by, "[locating] the prime targets for hosting habitable, terrestrial planets among our closest stellar neighbors."

      NASA recently selected TESS under the Astrophysics Explorer Program. The Explorer Program is NASA's oldest continuous program and has launched over 90 space missions. The Explorer Program has a long and stellar history of deploying truly innovative missions to study some of the most exciting questions in space science. With TESS, scientists will identify many nearby star systems with rocky planets in the habitable zone for further study by telescopes such as the James Webb Space Telescope.

      Since the 2010 "New Worlds, New Horizons" decadal survey, NASA has been strategic in looking for opportunities to expand exoplanet research and discoveries while being respectful of the decadal survey's recommendations. Hence, NASA's selection of TESS will help scientists to identify targets for study by JWST and a future, dedicated exoplanet mission. The design for a future dedicated exoplanet mission is still under study.

b. What role did Kepler's recent technical problems play in this decision?

The Kepler mission was fully successful, and the TESS mission builds on that success. Kepler's recent technical problems (associated with reaction wheels) did not play any role in NASA's selection of TESS.

7. The Space Telescope Science Institute indicated that a key technology for determining exoplanet habitability is the development of a high performance coronagraph to block a star's brightness so that measurements can be taken with a spectrograph to analysis the atmospheres and surfaces of exoplanets close to a star. How complicated is this endeavor? What would such a mission cost?

Earth sized planets in the habitable zone of a solar type star are very difficult to image. The planet is a billion times fainter than the star and, from our perspective; it lies very close to the star. NASA agrees that the key technology for determining exoplanet habitability is the development of a high performance coronagraph. That is why NASA is investing substantial funds in its Technology Development for Exoplanet Missions (TDEM) program, funding technologists who are working on at least five different possible coronagraph architectures.

NASA has begun studying the use of the 2.4m telescope assets made available to NASA by the National Reconnaissance Office (NRO). An excellent use would be for a mission that can exceed the decadal survey's science goals for wide field infrared survey telescope (WFIRST); the mission concept that uses one of the 2.4m telescope assets to exceed the decadal survey's science goals for WFIRST is called AFTA (Astrophysics Focused Telescope Asset). NASA is studying the addition of a coronagraph to the AFTA mission in order to demonstrate coronagraph technology. The use of the 2.4m telescope assets made available to NASA by the NRO makes the addition of a coronagraph feasible. The AFTA design reference mission incorporates a coronagraph for direct imaging and characterization of ice and gas giant exoplanets in the outer parts of planetary systems around the nearest stars. A telescope much larger than AFTA will be required to use a coronagraph to search the atmospheres of Earth-like exoplanets for spectroscopic signatures of life in their atmospheres.

The cost of a mission with a coronagraph depends on the science goals. A potential AFTA mission with a coronagraph would cost around $2B or more, depending on the science requirements, in FY 2013 dollars (plus launch vehicle). A more capable general-purpose exoplanet imaging mission would cost much more. NASA studies are underway to refine the cost estimates as a function of science capability.

8. The Space Telescope Science Institute indicated that JWST could be optimized for exoplanet research by using a starshade. How complicated is this endeavor? What would such a mission cost?

A starshade, also known as an external occulter, is a spacecraft that works to align with JWST when it is in orbit. The starshade would enable JWST to reveal the elusive habitable planets and possibly search for life. The starshade endeavor is very complicated, and the starshade has to be precisely positioned with respect to the JWST line-of-sight, which may be difficult to maintain for the periods needed to observe exoplanets. Also, the starshade is a large deployable structure that has to be precisely shaped and controlled to maintain that shape, so it is able to mask the light from the parent star.

No starshade is currently planned for the JWST mission. A study began in 2013, with a final report due in early 2015, to estimate the cost of a small, dedicated starshade mission that does not involve JWST.

9. What work have private organization conducted on education and public outreach initiatives related to exoplanet discoveries?

Numerous private organizations have used NASA's data and discoveries to conduct education and public outreach initiatives related to exoplanet discoveries. NASA does not have a complete list, since NASA freely shares all of its data and discoveries with the public and without restriction. Some private organizations the conduct education and public outreach using NASA exoplanet data and discoveries include:

- SETI Institute (Mountain View, California) conducts education and public outreach programs share the excitement of exoplanet discoveries and searching for life in the universe with people from all ages and various backgrounds. Several million people per year tap into SETI Institute's website and podcast radio show for cutting edge science, technology, and viewpoint.
- Boonshoft Museum of Discovery (Dayton, Ohio), Adler Planetarium (Chicago, Illinois), Museum of Natural History and Planetarium (Providence, Rhode Island), and Museum of Science (Boston, Massachusetts) have all used NASA Kepler's data and other NASA exoplanet discoveries to share with the public that our solar system is not alone in the universe.
- Las Cumbres Observatory Global Telescope Network (Goleta, California) is building a global network of telescopes for professional research but they will also be used for citizen science relating to exoplanets discoveries.

10. The National Academies' 2010 decadal survey recommended the improvement of the precision radial velocity method. How has this method improved since the report was issued? What are the steps that need to be taken for further improvement?

The precision radial velocity method is conducted from ground-based telescopes. NSF will respond to this question.

11. Please elaborate on the specific role that NASA's suborbital and Explorer programs have played in exoplanet exploration. Are there any NASA missions not currently used for exoplanet research that could have exoplanet applications?

The suborbital research program includes sounding rockets and stratospheric balloons. A suborbital rocket flight has been used to test a deformable mirror and a coronagraph on a stellar target; more experiments on rocket flights are expected in the future. The stratospheric balloon flight program has traditionally been very important in developing instrumentation for space experiments; there is currently one exoplanet balloon experiment under development, and several others have been proposed. NASA is developing an arc second pointing system for the balloon platform in support of future exoplanet experiments, and it has had two successful flights.

The suborbital Stratospheric Observatory for Infrared Astronomy (SOFIA) aircraft program is aimed in part at making exoplanet observations.

The Explorer Program has seen several proposals for study of exoplanets, and in April 2013 the Transiting Exoplanet Survey Satellite (TESS) was selected for a 2017 launch. TESS will survey the full sky to detect an expected 5000 transiting exoplanets. So the Explorer program has been, and will continue to be, an important contributor to exoplanet research.

It is worth noting that the spectacularly successful Kepler mission was originally selected as a Discovery Mission, a cost class above Explorers.

All NASA missions that can contribute to exoplanet research have been used to do so. These include Chandra X-ray Observatory, Hubble Space Telescope, Kepler Space Telescope, Spitzer Space Telescope, Stratospheric Observatory for Infrared Astronomy (SOFIA), Widefield Infrared Survey Explorer (WISE), and the Deep Impact Extended Investigation and Extrasolar Planet Observation and Characterization (also known as EPOXI). There are no NASA missions not currently used for exoplanet research that could have exoplanet applications.

12. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that between 2008 and 2013 preparations begin for a "space-borne astrometric mission capable of surveying between 60 and 100 nearby main sequence stars with the goal of finding planets down to the mass of Earth orbiting their parent star within the habitable zone." What progress was made towards achieving this goal? Are there limiting factors beyond budget constraints? What is the status of these preparations? What is the expected timeline of such a mission?

The Task Force is referring to the Space Interferometry Mission (SIM). Earlier, SIM had been initiated and recommended by the 1991 NRC decadal survey, and carried forward by the 2001 decadal survey. However, the 2010 decadal survey (p.16, note 2) stated that two previously recommended projects, one of them being SIM, "*are not included in the recommended program for the decade, following the committee's consideration of the strengths of competing compelling scientific opportunities and the highly constrained budget scenarios described in this report.*" SIM completed its technology development program in 2005, having met or exceeded the requirements for every one of the 8 key technology gates. Between 2005 and 2010, SIM was in Phase B, tasked with engineering risk-reduction, and preparing to proceed to a Preliminary Design review (PDR). After the 2010 decadal report appeared, the SIM project was closed out; there is currently no prospect for a SIM mission.

Since 2010 some new concepts for an astrometric mission have arisen, focusing solely on detecting exoplanets and measuring their masses (but not addressing the many other areas of astrophysics envisioned for SIM, thereby making the new concepts simpler and less expensive). These types of missions are attracting new interest in the US and Europe for the purpose of finding exoplanets and measuring masses around our nearest neighbor stars.

Astrometric missions will continue to be studied as potential future exoplanet discovery missions. NASA is investing in the technology necessary to enable such missions, and proposals for small astrometric missions are expected in response to future Explorer Program announcements of opportunity.

13. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that between 2008 and 2013, scientists engage in the technological development of "space-borne direct detection capabilities to find and characterize Earth-sized planets." Specifically, the recommendation notes the need for the development of advanced wavefront sensing and control, next-generation deformable mirrors, low-noise detectors, coronagraphic masks, ultraprecise optical surfaces, and validated diffraction modeling. Please describe the progress of these technological developments. Which have been achieved to a satisfactory level to operationalize for use in exoplanet discovery? Which still require work? Are there additional specific capabilities that are needed?

As recommended, a great deal of technology development has occurred in these areas, and these advances underpin the current embracement of a direct-imaging coronagraph for a potential Astrophysics Focused Telescope Asset (AFTA) mission by the Science Definition Team studying the use of the 2.4m telescope assets made available to NASA by the National Reconnaissance Office (NRO), although the telescope size for that potential mission limits its expected discoveries mainly to gas giant planets around nearby stars.

Specific developments include the following: advancements in wavefront sensing and control, with new algorithms being developed and employed on testbeds at NASA centers and universities; deformable mirrors, with more reliable electronic controllers and electrical connectors having been developed, and new types of compact deformable mirrors under development; low-noise detectors, using electron multiplication in the detector chip, before the charge encounters a noise-inducing amplifier; coronagraph masks, with new methods of adding dielectric layers to improve the performance of metal-on-glass masks, and several new types of vector vortex masks being developed with liquid crystal technologies, and also photonic crystal technologies, using a relatively newly discovered property of light, its ability to carry orbital angular momentum, in addition to its well-known property of intrinsic spin angular momentum; ultra-precise optical surfaces, in which computer-controlled deformable-lap polishing and ion etching have become more commonly available technologies; and diffraction modeling, in which new computer codes have been developed that fully include all known diffraction effects.

Nevertheless, more technology development is needed to enable a coronagraph on AFTA, as well as any follow-up Earth-detection and characterization mission. The two areas needing the most development are wavefront sensing and control and coronagraph masks; the other areas are either fully developed for AFTA, or need less work. Specifically, the most important technology development area for the potential AFTA mission is to select the optimum (science and cost) coronagraph design, from among the handful of candidates, and move it from the laboratory bench to an engineering demonstration level.

14. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that NASA establish a blue-ribbon panel to evaluate coronographic wavefront control concepts and ensure that no fundamental physical effect was overlooked in planning for an optical wavelength, direct detection mission. Was such a panel established? What were the results of their discussions? If not, what progress was made towards establishing such a panel?

NASA proceeded directly from the Task Force's Recommendation to establish a significant program for the development of the technologies needed for the coronagraphic detection of exoplanets. Direction from this program came from the NASA's Navigator Program (later renamed the Exoplanet Exploration Program) office, aided by a Technology Assessment Committee consisting of experts in instrumentation and space technology.

NASA provided significant funding to competitively selected scientists and engineers at Universities and NASA Centers. This effort has led to laboratory demonstrations of a number of different techniques for direct imaging at levels approaching those needed for detection of Earth-sized planets orbiting nearby stars. A number of these technologies are now at Technology Readiness Level (TRL) 3-4 and could be matured to TRL 5-6 in the next 3-4 years for use in future observatories.

15. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that NASA establish a blue-ribbon panel to evaluate direct detection by interferometry. Was such a panel established? What were the results of their discussions? If not, what progress was made towards establishing such a panel?

The community-based Exoplanet Program Analysis Group (ExoPAG), an analysis group of the NASA Advisory Council's Astrophysics Subcommittee, analyzed the relative merits of direct-imaging coronagraphs and interferometers, and found in February 2011 that in a fiscally constrained environment it would be prudent to pursue technology development for the coronagraph at the present time, deferring the interferometer to a later decade. Consequently, the interferometry option is not being pursued at this time.

16. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended a census of exo-zodi systems around solar type stars. Did such a census take place? If so, what were the results? If not, what progress was made towards achieving this goal?

Yes, one census of exo-zodi dust emission around solar-type stars has already been completed, and another, more advanced, census is currently underway. The first census was carried out with the Keck interferometer (using both 10-m telescopes to feed a single instrument and detector) on Mauna Kea, Hawaii, and published in 2011; the results for the 25 stars that were surveyed at mid-infrared wavelengths are that dust emission was indeed detected around 3 stars, but the remaining 22 stars had dust emission levels below the sensitivity limit of the interferometer, giving a statistical average of less than 50 times the amount of dust in the Solar System's zodi disk.

The second census is being carried out from 2012 to 2017, with the Large Binocular Telescope Interferometer (using both 8.4-m telescopes) on Mt. Graham, Arizona, with a goal of surveying 50 stars down to a level corresponding to 3 times the amount of dust in the Solar System, for each star, a level that is expected to be sufficiently low that a space-based imaging telescope will be able to detect an Earth-twin around a nearby star.

17. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended searching the nearest thousand M-dwarfs for transiting low-mass exoplanets with radial-velocity measured masses. What progress was made towards achieving this goal? Are there limiting factors beyond budget constraints?

Ground-based searches for transiting exoplanets are sponsored by NSF. The NSF will answer part of this question.

NASA has selected the Transiting Exoplanet Survey Satellite (TESS) for launch in 2017 to survey over 500,000 stars, looking for transiting exoplanets around bright, nearby stars. TESS's targets will include 1,000 of the closest M stars.

18. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that emphasis be placed on the development of near-IR spectrographs with one meter per second precision for radial velocity planet surveys of late M-dwarfs once feasibility at 10 meters per second has been demonstrated. What is the status of this recommendation?

The precision radial velocity method is conducted from ground-based telescopes. NSF will respond to this question.

19. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that operation of the Spitzer telescope continue as a "warm observatory" for characterizing low-mass transiting planets around main sequence stars. Is this recommendation feasible? If so, is NASA using Spitzer for this purpose?

Spitzer exhausted its cryogen, as expected, in May 2009, and has been successfully and productively operating in a "warm Spitzer" mode since that time. The science that remains in this mode uses the shorter wavelengths in the infrared region; these wavelengths are accessible only in space. During its warm mission, Spitzer has valuable contributions to exoplanet science by allocating a substantial fraction of its observing time to validation of exoplanet discoveries, particularly those provided by the Kepler mission

20. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended continued support for archival analysis of Spitzer, Chandra, Hubble, and ground-based data. What is the status of archival analysis of these data? Are there limiting factors beyond budget constraints?

NASA funds an active program of archival research with its 3 Great Observatories, (Spitzer, Chandra, Hubble). In particular, exoplanet scientists draw heavily from the Spitzer and Hubble archives. Results include using advanced imaging techniques to reanalyze Hubble images of stars that are now known to host planets. These images often predate the images used to first discover planets and can provide valuable constraints on exoplanet orbits. Archival Spitzer data have been used characterize the atmospheres of known transiting systems. NASA's primary ground-based data set comes from the Keck Telescope in which NASA is a 1/6 partner. NASA funds the Keck Observatory Archive, which provides access to images and spectra that have been used to characterize exoplanets.

Over the years, NASA has invested in the development and execution of an extensive array of space astrophysics missions, including the Agency's Great Observatories. The magnitude and scope of the archival data from those missions enables science that transcends traditional wavelength regimes and allows researchers to answer questions that would be difficult, if not impossible, to address through an individual observing program. To capitalize on this invaluable asset and enhance the scientific return on NASA mission investments, the Astrophysics Data Analysis Program (ADAP) provides support for investigations whose focus is on the analysis of archival data from NASA space astrophysics missions.

21. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended moving planetary system architecture studies and multiple-planet statistics beyond the 3 to 5 Astronomical Unit "ice-line" boundary for G-type stars by continuing long-time baseline Doppler spectroscopic studies in the next five years. Do you anticipate that this will be possible? What progress was made towards achieving this goal? Are there limiting factors beyond budget constraints?

The precision radial velocity method and ground-based microlensing surveys are conducted from ground-based telescopes. NSF will respond to this question.

22. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended launching a Discovery-class space-based microlensing mission to determine statistics of planetary mass and the separation of planets from their host stars as a function of stellar type and location in the galaxy. Do you think such a mission is possible? What barriers might there be to achieving this goal? Would there be an alternative means of obtaining the same statistics?

Gravitational microlensing from space was incorporated by the 2010 Decadal Survey as a key element of the highest ranking recommendation for space and is, indeed feasible. The highest priority of the decadal survey is a wide field infrared survey telescope (WFIRST). Microlensing is an integral part of the WFIRST mission concept. If a mission that realizes the science objectives of WFIRST were to go forward, it would be far more effective than a Discovery-class microlensing mission. A microlensing space mission is so highly productive compared to a ground-based version that there is no reasonable alternative.

23. What is the process by which NASA incorporates peer review and opinions from the scientific community into their policies and strategic plans related to exoplanets?

Investment choices first consider scientific merit. The Science Mission Directorate (SMD) uses open competition and scientific peer review as the primary means for establishing merit for selection of research and flight programs.

Active participation by the research community outside NASA is critical to success. SMD engages the external science community in establishing science priorities, preparation and review of plans to implement those priorities, analysis of requirements trade studies, conduct of research, and evaluation of program performance.

NASA asks the National Academy of Sciences to set strategic priorities through decadal surveys. NASA engages the science community through Federal advisory committees to provide advice on policies and strategic plans. This includes the Exoplanet Program Analysis Group (ExoPAG) of the NASA Advisory Council's Astrophysics Subcommittee and the Exoplanet Task Force of the Astronomy and Astrophysics Advisory Committee. NASA engages the science community through competitively solicited proposals and peer review to select specific science investigations and scientific participants to execute exoplanet missions and research.

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEES ON SPACE AND RESEARCH

"Exoplanet Discoveries: Have We Found Other Earths?"

Questions for the Record, Dr. John Grunsfeld, Associate Administrator, Science Mission Directorate, National Aeronautics and Space Administration

Questions submitted by Rep. Larry Bucshon, Chairman, Subcommittee on Research

1. **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?**

   There are many private sector contributors to the ground-based astronomy, such as private and public university systems and non-profit foundations. However, while those contributors provide a wide range of facilities that are important for advancing exoplanet science, the support they provide for the scientists who ultimately conduct the scientific investigations using those facilities is much more limited. Government support is, therefore, crucial to effectively leverage the contributions of the private sector in this field.

   There are two major differences between government-funded and private sector-funded exoplanet research: (1) source of money, and (2) sizes of the projects. Only the federal agencies can sustain the long-term programs of technology development, facility (observatory or mission) construction, and operations that are necessary to accomplish the goals of exoplanet research. Space-based observatories are crucial to realizing the scientific goals of exoplanet exploration and have historically been the domain of the Federal Government.

   Government-funded and private sector-funded exoplanet research carry the same weight in the scientific community.

2. **What techniques are used for planet detection and characterization? How do you hope to specifically refine existing techniques going forward? What potential do these techniques have that has not yet been realized, or that you think will be better realized in the coming years? Are there any techniques that can be performed by amateur astronomers?**

   The planet detection and characterization techniques are: (1) radial velocity technique (uses Doppler Shift to detect star's wobble as planet orbits); (2) direct imaging (uses a coronagraph or occulter to block light from central star so the much fainter planet nearby can be discerned); (3) transit technique (uses change in star's brightness as planet goes in front or behind star); and, (4) microlensing (uses Einstein's gravitational bending of light to find planets orbiting distant starts).

We hope to refine the existing techniques by continuous research and testing of the planet detection and characterization techniques. We continue to invest, both time and resources, in the innovative technologies.

The potential benefits of the planet detection and characterization techniques will be better realized in the coming years as innovative technologies and larger telescopes optimized for exoplanet detection enable scientists to find fainter planets such as rocky Earth-like ones orbiting closer to nearby stars.

Almost exclusively, the signals of exoplanets are so faint that their detection is beyond the capabilities of the equipment available to even advanced amateur astronomers. However, citizen science projects, such as Planethunters.org, are already providing a valuable contribution to the analysis of NASA data for new exoplanets.

3. What have we learned about planet formation from studying exoplanets?

Recently, from NASA's Hubble Space Telescope, astronomers have found compelling evidence of a planet forming 7.5 billion miles away from its star. This is far beyond the distance at which planets have traditionally been thought to form, and challenges current theories about planet formation. The suspected planet is orbiting the diminutive red dwarf TW Hydrae, a popular astronomy target located 176 light-years away from Earth in the constellation Hydra the Sea Serpent. Hubble Telescope's keen vision detected a mysterious gap in a vast protoplanetary disk of gas and dust swirling around TW Hydrae. The gap is 1.9 billion miles wide and the disk is 41 billion miles wide. The gap's presence likely was caused by a growing, unseen planet that is gravitationally sweeping up material and carving out a lane in the disk, like a snow plow.

Planets are thought to form over tens of millions of years. The buildup is slow, but persistent as a budding planet picks up dust, rocks, and gas from the protoplanetary disk. A planet 7.5 billion miles from its star should take more than 200 times longer to form than Jupiter did at its distance from the sun because of its much slower orbital speed and the deficiency of material in the disk. Jupiter is 500 million miles from the sun, and it formed in about 10 million years.

TW Hydrae is only 8 million years old, making it an unlikely star to host a planet, according to this theory. There has not been enough time for a planet to grow through the slow accumulation of smaller debris. Complicating this theory further is that TW Hydrae is only 55 percent as massive as our sun. An alternative planet formation theory suggests that a piece of the disk becomes gravitationally unstable and collapse on itself. In this situation, a planet could form more quickly, in just a few thousand years.

4. What is the single most important technological advancement that is needed to further exoplanet research? What advancement should be our highest priority?

Earth sized planets in the habitable zone of a solar type star are very difficult to image. The planet is a billion times fainter than the star and, from our perspective; it lies very close to the star. The key technology to further exoplanet research is the development of a high performance coronagraph. That is why NASA is investing funds in its Technology Development for Exoplanet Missions (TDEM) program, funding technologists who are working on at least five different possible coronagraph architectures. Each architecture uses a different method to advance the three metrics for success of coronagraph technology: how faint a planet can be seen (this called the contrast ratio), how close to the star can a planet be seen (this is called the inner working angle), and how many different wavelengths does the coronagraph work at (this is called the spectral range).

NASA has begun studying the use of the 2.4m telescope assets made available to NASA by the National Reconnaissance Office (NRO). An excellent use would be for a mission that can exceed the decadal survey's science goals for wide field infrared survey telescope (WFIRST); the mission concept that uses one of the 2.4m telescope assets to exceed the decadal survey's science goals for WFIRST is called AFTA (Astrophysics Focused Telescope Asset). NASA is studying the addition of a coronagraph to the AFTA mission in order to demonstrate coronagraph technology. The use of the existing 2.4m telescope assets makes the addition of a coronagraph feasible. The smaller and more limited version of WFIRST described in the decadal survey cannot accommodate a coronagraph.

Questions from Ranking Member Donna Edwards to Dr. Grunsfeld
"Exoplanet Discoveries: Have We Found Other Earths?"

1. **To what extent would the telescopes donated by the NRO to NASA enhance WFIRST's ability to detect exoplanets? How will NASA determine the relative value of that enhanced capability versus making other investments in exoplanet or planetary science research? When will a decision be made on initiating a WFIRST mission?**

   A microlensing exoplanet survey with a wide field infrared survey telescope (WFIRST) that uses one of the 2.4m telescope assets (a mission concept referred to as Astrophysics Focused Telescope Asset, or AFTA) is substantially superior to previous WFIRST designs, resulting in 25% more planet detections, significantly better sensitivity to small planets, and enabling detailed characterization of the majority of the detected planetary systems. The development of a coronagraph for AFTA directly responds to the decadal survey's first medium scale priority to mature technology development for exoplanet imaging, providing an important stepping-stone towards building a future telescope capable of searching nearby planets for signs of life.

   The decadal survey prioritized a wide field infrared survey telescope over an exoplanet mission for this decade; NASA accepts that prioritization.

   The Administrator instructed the Science Mission Directorate to continue pre-formulation activities for a wide field infrared survey telescope mission using the 2.4m telescope assets. No decision on a future wide field infrared survey telescope mission is expected until early 2016.

2. **NASA recently selected the Transiting Exoplanet Survey Satellite (TESS) as an Explorer mission.**

   - **How does TESS's goal differ from Kepler's?**

   TESS will use an array of wide-field cameras to perform an all-sky survey to discover transiting exoplanets, ranging from Earth-sized planets to gas giants, in orbit around the brightest stars in the Sun's neighborhood. With TESS, it will be possible to study the masses, sizes, densities, orbits and atmospheres of a large cohort of small planets, including a sample of rocky worlds in the habitable zones of their host stars.

   Kepler's primary goals are to determine how abundant planets are in our galaxy, what the distribution of sizes and orbits of those planets are, and ultimately what fraction of stars might harbor potentially habitable, Earth-sized planets.

   NASA's Kepler spacecraft has recently uncovered the existence of many smaller exoplanets, but the stars Kepler examines are faint and difficult to study. In contrast, TESS will examine a large number of small planets around the very brightest stars in the sky. The TESS legacy will be a catalog of the nearest and brightest main-sequence stars hosting transiting exoplanets, which will be the most favorable targets for detailed investigations by future missions including the James Webb Space Telescope (JWST).

While Kepler has taught us about the abundance of planets of all sizes in one particular region of our galaxy, TESS will reveal the exoplanets that are nearest to our Solar System.

- **Are there any synergies between TESS's projected mission and that planned for the James Webb Space Telescope (JWST)?**

  Yes, there are potential synergies between TESS and JWST. That is, TESS would undertake an all-sky search for transiting exoplanets. TESS would discover the nearest bright stars and discover the thousands of new planets – including Earth-sized, rocky planets – that would be ideal candidates for characterization by future missions such as JWST.

  Once appropriate exoplanets are identified, JWST will use transit spectroscopy to determine atmospheric and physical properties of planets ranging in size from Jupiters to Super Earths. Also, JWST will use direct imaging to find and study young (i.e., still warm) Jupiters and Saturns as well as rings of dust, and icy/rocky planetessimals located far from the parent star in many exoplanet systems.

- **Are there any planned missions that would have the capability to establish the signatures of certain molecules in the atmospheres of nearby planets that could be used to infer the presence of extraterrestrial life on a planet? If not, would this be a candidate to be considered in the next astrophysics Decadal Survey?**

  Yes, the James Webb Space Telescope would partially do so, but only for transiting planets around nearby stars. A dedicated exoplanet mission is required to image and characterize planets (including non-transiting planets) that are close to the parent star and/or orbit stars that are beyond the Sun's neighborhood.

3. **Shortly after the hearing, Kepler went into safe mode, likely because of the loss of another reaction wheel. What is NASA considering to do to in attempting to restore Kepler to full operational capability? If operated in a degraded mode, what science will still be accomplished?**

   In response to Kepler's second reaction wheel failure, the agency has taken the following actions:

   - The spacecraft has been placed into a loosely-pointed, thruster-controlled mode to preserve its propellant. In this mode the spacecraft is using fuel at a rate lower than when it was collecting science data, with an on-board supply capable of lasting 4-5 years. This allows time for engineers to investigate wheel recovery options or alternative operating modes.

   - The Kepler project has established an Anomaly Resolution Team with participation from industry and multiple NASA centers. This team has commenced discussions and identified initial tests to characterize the state of the wheels and begin a potential recovery process. At present, the team feels it is unlikely that either of the failed wheels will recover full performance, or even degraded performance for an extended period, but may regain sufficient performance to make the recovery efforts worthwhile.

- The agency has established a 2-wheel operations tiger team through the NASA Engineering and Safety Center (NESC), with participation from multiple NASA centers, industry and academia. This team is working with the Kepler mission to investigate means of operating the spacecraft using only the remaining 2 wheels, thrusters and solar pressure. This team will identify potential operating modes and weigh the performance of each to determine if the baseline mission can be resumed. If not, the team will identify what performance can be achieved.

- The Kepler Project has initiated steps to identify, solicit and evaluate alternative scientific opportunities if the spacecraft pointing on 2 wheels is insufficient to continue the exoplanet mission. Alternative mission science objectives might include exoplanet science, general astrophysics, a search for near Earth objects, or other science. This process is in the early stages of development, as any eventual decision will be strongly influenced by the spacecraft performance achieved through the activities described above and the cost to implement it.

4. **Should the information being disseminated on discoveries of Earth-sized planets be enhanced so that the public recognizes the challenges of identifying the existence of Earth-like conditions on these planets? How can the public's interest be engaged on a sustained basis in an environment where repetitive "discovery" announcements could lead to diminished interest? If the discovery of Earth-like planets is likely the only item of interest to the public, what can be done to address such expectations? How are budget reductions to NASA's education and public outreach (EPO) activities affecting the agency's ability to engage the public?**

NASA is doing its best to disseminate discoveries of Earth-sized planets on press releases, social media, and traditional media sources such as NASA TV. Hundreds of thousands of people access NASA's press releases, social media, and traditional media sources to learn about exoplanets discoveries.

Concerning the Administration's FY 2014 budget, NASA's Office of Education will lead the Agency's coordination with other Federal agencies in pursuit of the Administration's STEM education goals.

NASA's education portfolio will focus on four priorities, which will contribute toward the Administration's goals for STEM education: (1) STEM Engagement; (2) NASA Internships, Fellowships, and Scholarships; (3) Educator Professional Development; and (4) Institutional Engagement. In a new approach, NASA will consolidate the education functions, assets and efforts of the Mission Directorates, Offices and Centers into a single coordinated STEM Education and Accountability Project (SEAP).

As part of NASA's STEM inter-agency coordination effort, NASA will ensure that the Agency's assets are put to use effectively in support of the STEM activities that will be directed by the National Science Foundation, the Smithsonian Institution, and the Department of Education.

NASA will make its rich content knowledge and other assets available to these agencies as they facilitate federal STEM education activities through the Administration's CoSTEM process for agency coordination, bring NASA's inspirational activities to a broader audience. This includes the infrastructure necessary to support the rigorous collection, evaluation, and dissemination of evidence of NASA's contributions towards the achievement of the wider STEM goals.

5. **What, if any, opportunities exist to collaborate with international space agency partners on future exoplanet research? What capabilities might such partnerships offer to help advance this area of science?**

The European Space Agency (ESA) is considering exoplanet missions in their Cosmic Vision Programme. NASA and ESA have a strong working relationship, and NASA's Science Mission Directorate (SMD) would like to collaborate with ESA on future exoplanet missions.

Such partnerships offer the opportunity to realize scientific advances in the study of exoplanets while sharing the cost with a partner. NASA's capabilities are equal to, or exceed, those of ESA for studying exoplanets.

Responses by Dr. Dr. James Ulvestad

Exploplanet Discoveries: Have We Found Other Earths?
Response to Questions For the Record
Dr. James S. Ulvestad, Division Director
Division of Astronomical Sciences (AST)
National Science Foundation
June 19, 2013

Questions submitted by Rep. Steven Palazzo

1. How do NSF, NASA, and other entities coordinate research amongst themselves?

A: NSF, NASA, and DOE coordinate their activities under the auspices of the Congressionally chartered Astronomy and Astrophysics Advisory Committee, which is mandated to meet four times per year and report annually to Congress. In addition, NSF and NASA program officers communicate frequently regarding individual investigator proposals that are submitted to the agencies, to ensure that duplication of effort is minimized in the funding of exoplanet and other research. A general meeting of the relevant NSF and NASA program officers was held in early April to facilitate this year-round cooperation. NSF separately coordinates with DOE on specific projects such as the Large Synoptic Survey Telescope and the Dark Energy Survey. Both of these projects are coordinated via a Joint Oversight Group that is chartered for each project, and that meets either biweekly or monthly.

2. What new capabilities does the Atacama Large Millimeter/Submillimeter Array (ALMA) provide that were not previously available? What research do we hope to fulfill using this tool?

A: ALMA provides the most sensitive millimeter and submillimeter wavelength imaging telescope, by two orders of magnitude, at the best observing site on Earth, for the investigation of radiation from cold gas and dust in the universe. Its angular resolution will be similar to that of the Hubble Space Telescope, again more than an order of magnitude better than any previous millimeter/submillimeter telescope. The specifics of the research to be done by ALMA will be governed by proposals from individual investigators that are reviewed by their peers, with the best research to be awarded time on the telescope. With respect to exoplanets, it is anticipated that this research will be focused on the imaging of the dust disks out of which such planets form, around nearby stars. This imaging will include measurements of the motion of the disks, assessment of gaps in the dust that are created by the gravitational influence of planets, analysis of the gas and dust composition and temperature in the disks, and comparison of all these data to theoretical models of planet formation.

3. What work have private organizations conducted on education and public outreach initiatives related to exoplanet discoveries?

A: Universities—both private and public—have a very significant impact in this area, through the efforts of academic departments and individual faculty, who provide public presentations and incorporate research results into regular course materials. A small fraction of these activities are supported directly by NSF as "broader impacts" of specific research projects; a much larger fraction comprise volunteer or institutionally funded efforts. Planetaria and science museums, many of which are privately funded in whole or in part, have produced a variety of educational planetarium shows on exoplanets. Some private observatories offer lecture series for the public covering all areas of astronomy including exoplanet research. Some individual observatories have developed educational materials (e.g., the Las Cumbres Observatory Global Telescope Network), but NSF does not have any information on how widely these materials have been adopted. Other private organizations are developing materials that might be regarded as educational as part of their broader efforts to raise funds to support research and other activities. Finally, major broadcast media organizations (e.g., Discovery Communications) continue to produce programming concerning exoplanet discoveries for the mass market. All of these efforts draw heavily on data products and other materials produced directly from federally funded research.

4. The National Academies' 2010 decadal survey recommended the improvement of the precision radial velocity method. How has this method improved since the report was issued? What are the steps that need to be taken for further improvement?

A: The discovery of exoplanets analogous to Earth by the radial velocity method requires radial velocity precision of 0.05 to 0.1 meters per second (hereafter m/s). The precision of these measurements was approximately 5 m/s in 2000, and had progressed to a typical value of 1 m/s by 2010. NSF/AST is funding multiple instrument development efforts, including innovative approaches, that are on track to reach the 0.1 m/s regime during this decade; these are funded through the AST program in Advanced Technologies and Instrumentation as well as the NSF-wide program in Major Research Instrumentation. Primary areas of development that are being funded include the stability of spectrographs as temperature and orientation change, as well as providing precision wavelength calibration systems (e.g., laser "combs") that allow very accurate and repeatable measurement of the wavelengths of the spectral lines used to infer stellar radial velocities. Funding of the implementation of precision radial velocity spectrographs is beyond the scope of the technology-development programs; see the discussion of the Mid-Scale Innovations Program below in response to a question from Representative Edwards. As the technical capabilities approach 0.1 m/s, an aspect that must not be neglected is an improved understanding of the stars themselves; motions in the stellar atmospheres connected to their magnetic fields and the upwelling of material from inside the stars can cause apparent motions that must be understood in order to deduce the stellar motions due to the gravitational forces of the unseen planet(s). NSF anticipates that studies of such host star properties in order to model the effects on radial-velocity measurements are likely to become more common in the regular research grants program over the next decade.

5. The National Academies' 2010 decadal survey noted that the period from 2010-2015 would see the completion of ground based mid-infrared interferometric instrumentation designed to study the dusty disks surrounding stars. What is the status of development of these instruments?

What improvements still need to be made? How has their development furthered our study of exoplanets?

A: NSF funded work on the Infrared Spatial Interferometer, a path-finding instrument on Mount Wilson, for a number of years. More recently, work on mid-infrared interferometry has been funded mostly by NASA. The two primary locations of the NASA efforts have been the Keck Interferometer (now closed) on Mauna Kea and the Large Binocular Telescope (LBT) Interferometer on Mount Graham, in Arizona. Operation of such interferometers is often difficult because the technique has low sensitivity, and hence is most useful for relatively bright stars. The mid-infrared interferometers have contributed important information to our understanding of the debris disks where planets may exist around newly forming stars, but it is not a simple matter to distinguish exoplanets from clumpiness in these disks.

6. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended a census of exo-zodi systems around solar type stars. Did such a census take place? If so, what were the results? If not, what progress was made towards achieving this goal?

A: This recommendation was largely focused toward a potential future NASA mission that involved a coronagraphic imager blocking the light of the parent star in order to image planetary systems. NASA has been carrying out studies of exo-zodiacal light using the Keck Interferometer and the LBT Interferometer. Results have been published in numerous papers, such as that by Millan-Gabet et al. in *The Astrophysical Journal* in 2011 (Volume 734, page 67). Further details about how the results of exo-zodiacal light studies meet NASA goals should be supplied by NASA.

7. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended searching the nearest thousand M-dwarfs for transiting low-mass exoplanets with radial velocity measured masses. What progress was made towards achieving this goal? Are there limiting factors beyond budget constraints?

A: NSF is funding several projects that are working toward this goal, including MEarth and the Habitable Zone PlanetFinder. The MEarth project is using eight moderate-sized (16-inch aperture) robotic telescopes in Arizona to survey the thousand nearest M-dwarf stars in order to find new Earth-like exoplanets, and this team discovered the first super-Earth exoplanet, GJ 1214b. Masses of planets are deduced from measured radii via the "transit method" combined with modeling predictions. The NSF also is funding the Habitable Zone Planet Finder, an instrument under construction, which will use the radial velocity technique to survey several hundred nearby M-dwarf stars in order to find new exoplanets. The Habitable Zone Planet Finder will consist of a near-infrared spectrograph capable of 1-3 m/s precision to be used with the 10-m Hobby-Eberly Telescope in Texas, and is expected to be capable of finding terrestrial mass planets around the majority of the least massive nearby M-dwarfs. NSF also funds several projects that are making in-depth observational and theoretical studies of hundreds of M-dwarf stars in order to develop sophisticated databases that will be needed to analyze the anticipated low-mass exoplanets around M-dwarfs. In the space realm, NASA has recently announced the selection of the Transiting Exoplanet Survey Satellite (TESS), which is relevant to this question; we will leave description of that mission to NASA.

8. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that emphasis be placed on the development of near-IR spectrographs with one meter per second precision for radial velocity planet surveys of late M dwarfs once feasibility at 10 meters per second has been demonstrated. What is the status of this recommendation?

A: Successful response to this recommendation is well in hand, and achievement of 1 m/s precision is becoming relatively common. Precision better than 1 m/s now has been demonstrated by an awardee in the NSF/AST Advanced Technologies and Instrumentation program, using a 1.5 m (60-inch) telescope in the red region of the spectrum. Developments aimed at improving to the 0.1 m/s level have been discussed in the response to a previous question.

9. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended adding a single two meter telescope to increase the efficiency of a ground-based microlensing network. Has this taken place? If so, has this addition increased the efficiency of ground-based microlensing? If not, is there a time frame for adding the 2 meter telescope? What progress was made towards achieving this goal? Are there limiting factors beyond budget constraints?

A: This recommendation was targeted at enhancing the capabilities of an existing international effort involving (at the time) observatories in Australia and Chile; the intent was to add a third telescope in South Africa. NSF has not funded the construction of such a telescope, in part because the 2010 Decadal Survey recommended microlensing as a science priority for large space-based, rather than ground-based, telescopes. In 2012 the Korean Astronomy and Space Science Institute (KASI) announced a plan to build a Korean Microlensing Telescope Network, consisting of 1.6-meter telescopes in Australia, Chile, and South Africa, and awarded Ohio State University (OSU) a contract for construction of the cameras. An OSU press release states that the telescopes and cameras are scheduled to be in place before the end of 2014.

10. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that ground-based capabilities such as extreme adaptive optics (AO, a technology to reduce wavefront distortions) be implemented in the lab and on eight meter class telescopes. Has extreme AO been implemented according to these recommendations? What progress was made towards achieving this goal? Are there limiting factors beyond budget constraints?

A: Extreme Adaptive Optics (hereafter ExAO) is a technique whereby the image of a host star is concentrated into a very small angular region by making real-time corrections to the distortions caused by the Earth's atmosphere, and then a coronagraphic occulting disk is used to block out the light of the parent star. ExAO was an important topic of study at the Center for Adaptive Optics, funded by NSF for 10 years beginning early in the last decade. This research has produced results in the form of advanced Adaptive Optics systems on the Keck 10m telescopes on Mauna Kea. An advanced ExAO system, the Gemini Planet Imager, is undergoing final acceptance testing at present before being shipped to the Gemini-South 8m telescope later this year for transition to full operations in 2014. (NSF is the majority partner in the International Gemini Observatory.) Understanding the point-spread function of a complex optical system on a telescope is a major requirement of any ExAO system; a recent NSF award to the team at the University of Hawaii is designed to address characterization of the point-spread function in a systematic way. Limiting factors in the development of ExAO will include the limits to the overall stability of a very complex optical system, as well as the engineering implementation of applying complex corrections in real time using moving systems on an operational telescope.

11. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended continued support for archival analysis of Spitzer, Chandra, Hubble, and ground-based data. What is the status of archival analysis of these data? Are there limiting factors beyond budget constraints?

A: NSF continues to provide individual investigator and collaborative grants for analysis of archival data through the Astronomy and Astrophysics Grants program. NSF routinely receives proposals in this program for the support of archival analysis of data from Spitzer, Chandra, Hubble, and other NASA missions, as well as a variety of ground-based telescopes. Such research covers all areas of astronomy, not just exoplanets. Particularly noteworthy among the ground-based telescopes is the Sloan Digital Sky Survey (SDSS), funded partially by NSF; NSF funds a number of research grants each year that make use of SDSS data for a variety of astronomical research. In recent years, since data have been released from NASA's Kepler satellite, NSF has begun receiving, and funding, proposals to analyze exoplanet data from the Kepler archive. Beyond purely budgetary limitations, which are significant, there is increasing recognition that data management and preservation decisions will grow in complexity and importance in the future, as new observatories begin to generate massive data streams.

12. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended moving planetary system architecture studies and multiple-planet statistics beyond the 3 to 5 Astronomical Unit "ice-line" boundary for G-type stars by continuing long-time baseline Doppler spectroscopic studies in the next five years. Do you anticipate that this will be possible? What progress was made towards achieving this goal? Are there limiting factors beyond budget constraints?

A: Several groups of investigators are making good progress toward this goal, and some have measurements approaching 15 years of coverage of planetary orbits beyond the "ice-line" boundary. Funding from both NASA and NSF has been used in such studies. It is likely that one of the limiting factors in continuing such long-term studies will be the availability of sufficient observing time on ground-based telescopes. As the population of known exoplanets grows beyond 1,000, the studies of newly discovered systems may begin to supplant some of the long-term monitoring efforts on oversubscribed telescopes.

13. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that the next five years see the construction of a 30 meter telescope to do optical direct detection of giant planets. Do you think construction of such a telescope is likely to take place in the next five years? Would this be an ideal project for international collaboration? Why or why not?

A: There currently are three international projects, two with substantial US involvement, that seek to construct large optical telescopes with apertures between 20 and 40 meters in diameter. These are ideal projects for international collaboration, because the expense and complexity of such telescopes places them beyond the reach of most national astronomy programs. Owing to the expense of these large telescopes ($1-2 billion), none of them has yet started construction, and none will be on line until after 2020. Although the 2010 astronomy and astrophysics decadal survey recommended a 25% federal investment in such a large telescope, this investment was their third-ranked priority for a large ground-based astronomy investment. Given current fiscal realities, NSF has stated that it would not be able to make a major construction investment in a 30m-class telescope during the current decade. However, NSF did issue a solicitation for partnership planning for eventual community involvement in such a large telescope, and made a partnership planning award this year, to the Thirty Meter Telescope Corporation. In the meantime, the International Gemini Observatory, in which NSF is the majority partner, has nearly completed a new instrument called the Gemini Planet Imager, which will become operational on the Gemini-South telescope during 2014. This instrument will be capable of imaging giant planets in orbits beyond the orbit of Jupiter around stars like our own Sun.

14. The report of the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force recommended that the next five years see the implementation of next-generation high spatial resolution imaging techniques on ground-based telescopes. Do you think implementing such techniques is feasible? Are there limiting factors beyond budget constraints?

A: Advanced imaging techniques are feasible; in fact, it is surprising how well large ground-based telescopes with advanced adaptive optics systems can perform relative to space-based telescopes. One limiting factor in producing high spatial resolution imaging is the ability to design and build sufficiently accurate and complex adaptive optics systems. The distortion of astronomical images for a ground-based telescope actually is caused by a combination of effects occurring from within the observing dome all the way to the top of the Earth's atmosphere; different techniques must be used simultaneously to correct for each of the effects. The various atmospheric effects contribute to significant changes in the telescope point-spread function on all timescales; this point-spread function must be calibrated and corrected continuously in order to enable the imaging of faint exoplanets. The design and operation of an adaptive optics system that simultaneously optimizes all corrections is enormously challenging, particularly when it is to be installed on an existing telescope that has fixed structural and optical characteristics.

Questions submitted by Rep. Larry Bucshon

1. What major lessons and discoveries have been gleaned from NSF-funded research regarding exoplanet interiors and atmospheres?

A: From the discoveries of the first exoplanets, researchers saw evidence for solar systems very different than our own – with gas giants very near their parent star having orbits measured in days rather than in years. More recent advances include (1) the basic chemical composition of upper atmospheres that is measured for many planets, revealing molecules such as carbon monoxide, carbon dioxide, hydrogen cyanide, and water; (2) atmospheric temperature and pressure profiles determined from detailed modeling of exoplanet data; (3) limits on the irradiation of upper atmosphere from the parent star; and (4) recently detected evidence for changes in exoplanet atmospheres over time periods as short as months.

2. It is my understanding that the proportion of exoplanet-related grants receiving funding at NSF is decreasing. What are your metrics for success in evaluating a project? Are there any steps that can be taken to address this issue?

A: The proportion of exoplanet proposals receiving funding, relative to other areas of astronomy, is actually increasing because of the increased demand by exoplanet researchers. However, the funding rate of all astronomy grant proposals is going down because of increasing demand and constrained budgets. Because of this trend, we expect to fund no more than 1 of every 8 exoplanet proposals in Fiscal Year 2013. The funding rate can be increased by restricting the submission of grant proposals, reducing grant award size, or increasing available funding.

In order to assess the likelihood of success of a research proposal, each proposal is peer-reviewed by community scientists using merit-based criteria that are focused on intellectual merit and broader societal impacts to society of the project. Following the award of funding, immediate metrics for evaluating success are primarily in the form of NSF program officer review of annual reports provided by the investigators. On the longer term, the primary metrics of success are provided by the scientific community in two ways. First, research results are submitted for publication in journals that are reviewed by expert colleagues in the field, and only successful and meaningful research is accepted for publication. Second, future grant proposals by the same investigators are reviewed based on the promise of success in the proposed research, and a major component of this review is an assessment of whether the investigators' past research in the field has (or has not) resulted in significant scientific advances.

3. What techniques are used for planet detection and characterization? How do you hope to specifically refine existing techniques going forward? What potential do these techniques have *that has not yet been realized, or that you think will be better realized in the coming years? Are there any techniques that can be performed by amateur astronomers?*

A: The two most important techniques used for planet detection and characterization over the last 15 years have been the radial velocity technique (finding planets and their masses by their gravitational influence on their host stars) and the transit technique (finding planets and their size and brightness by virtue of their passage across the face of the host star, as seen from Earth). Other methods that have found many fewer planets include gravitational microlensing (whereby the gravitational field of a planet causes the variation in brightness of a background star) and direct imaging. Answers to questions from Representative Palazzo have commented extensively on the work under way to improve these techniques via higher-precision velocity measurements and advanced adaptive optics capabilities. Such techniques typically are beyond the reach of amateur astronomers. However, well-trained amateurs can contribute significantly to exoplanet detection and characterization by measuring the transits of exoplanets around relatively bright stars using inexpensive instrumentation on small telescopes. Perhaps the best avenue for amateur participation is through so-called "citizen science" projects, whereby average citizens can use publicly available data sets to participate in making true discoveries that are missed by the much smaller population of professional astronomers working on exoplanets. An example of such a citizen science effort is the Planet Hunters project, which is described at *http://exoplanets.astro.yale.edu/science/citizenscience.php*.

4. What have we learned about planet formation from studying exoplanets?

A: Scientists have known for many decades that planets form from disks of gas and dust that are left over from the formation of their parent stars. In studies of our own Solar System, scientists believed that they could read the past conditions in that protoplanetary disk from the present-day sizes and orbits (i.e., locations) of the planets. There were hints that this might not be right, but it wasn't until astronomers began seeing the tremendous diversity in exoplanetary systems—starting with the "hot Jupiters" surprisingly close to their parent stars—that they saw the inherent limitations in extrapolating too broadly from the characteristics of our own Solar System. The studies of exoplanets have shown how much planetary orbits can change, and have led to new theoretical models of how planetary systems form and evolve. The essential details of these models are very complicated and still not understood. For example, the idea that planets more massive than Jupiter may commonly form far from their parent stars, then migrate inward toward those parents, may have a huge impact on the possible existence of life on any rocky planets in the same system. So far, our Solar System appears to be more orderly than most of the exoplanet systems that have been identified, but observational techniques are just approaching the capabilities that would allow detection and characterization of solar systems looking similar to our own.

5. What is the single most important technological advancement that is needed to further exoplanet research? What advancement should be our highest priority?

A: One should be careful not to mistakenly think that there is always a single obstacle to discovery. More often the new data that a technological development provides make sense only in the context of other developments happening at the same time. For exoplanets, the near-term high priorities are adaptive optics systems that can produce stable and very well characterized images, and the perfection of high precision radial velocity spectrographs and calibration sources. Both of these have been identified by NSF as important and worthy of significant funding. But not to be neglected are the technological and engineering advances required simply to realize large telescopes such as the Atacama Large Millimeter/Submillimeter Array and the various concepts of optical telescopes in the 30m class. Successful design, construction, and operation of such telescopes rely on a range of advances in structural engineering, reduction of systematic effects caused by the telescopes themselves (e.g., turbulence induced by the telescope dome), and low-noise detectors in the optical, infrared, and radio regimes.

6. How does the current budget situation impact Senior Reviews at NSF that determine what telescopes should be decommissioned in favor of new investments and capabilities?

A: Senior Reviews do not determine which telescopes should be decommissioned; instead, the reports of such review committees are recommendations to NSF. The actual process to close and decommission an NSF facility would be complex and would involve input from multiple stakeholders beyond NSF staff and the review committee. Both the 2006 Senior Review and the 2012 Portfolio Review explicitly recommended divesting certain telescopes, i.e., significantly reducing NSF/AST's contribution to their operating costs. Decommissioning of telescopes would be the least desirable option, since actual decommissioning would incur very significant additional costs. New partnerships or re-purposing of telescopes are far more desirable outcomes, though not always possible.

The Portfolio Review Committee's recommendations for divestment were driven primarily by the current budget situation, together with the need for natural evolution in a healthy program. All of the facilities recommended for divestment are productive, and in some cases unique, telescopes still capable of cutting-edge science and providing telescope access to the majority of US astronomers. The Portfolio Review report emphasized that divestment was necessary in the near term to meet commitments to the operation of new capabilities now nearing their operational states, while maintaining a balanced program that could still support basic research and technology development through healthy small grants and mid-scale programs.

7. What is the status of interagency coordination between DOE and NSF with regards to the Large Synoptic Survey Telescope and other exoplanet projects? How does this relationship compare to NSF's relationship with NASA?

A: The Large Synoptic Survey Telescope (LSST) is not primarily an exoplanet project, but is a strong example of interagency coordination. NSF and DOE have a signed Memorandum of Understanding regarding the scope of work and funding that each agency will deliver and manage for LSST, as well as a formal Joint Oversight Group (JOG) that meets biweekly to discuss coordination. The two agencies also conduct joint reviews and/or participate in the other agencies formal reviews of LSST. Similar coordination at a smaller scale takes place on smaller projects such as the Dark Energy Survey, where a DOE camera has been installed on an NSF telescope in Chile. NSF and NASA do not currently have large hardware projects on which they are executing joint construction, so there are no JOGs in operation between the two agencies for the execution of astrophysics programs. However, NASA does execute its long-duration balloon program in Antarctica making use of NSF logistics facilities, under a signed MOU between the agencies, and is about to use NSF facilities in New Zealand to stage southern flights for the NASA Stratospheric Observatory For Infrared Astronomy (SOFIA). NSF and NASA recently initiated a Theoretical and Computational Astrophysics Network (TCAN) program, responsive to a recommendation of the 2010 National Academies decadal survey, and carried out a joint review of the proposals responding to a solicitation. A blanket Memorandum of Agreement between NSF and NASA was modified to accommodate this TCAN effort.

8. The Astronomy and Astrophysics Advisory Committee's yearly report for 2013 recommended that NSF request a report led by the National Research Council's Committee on Astronomy and Astrophysics to help define a revised national ground based optical/infrared (OIR) system. Have you requested this report? If so, when can we expect the results? If not, why?

A: NSF is in discussion with the Committee on Astronomy and Astrophysics (CAA) regarding the exact charge and content of a study on the ground-based OIR system. NSF has presented a draft set of deliverables to the National Research Council, but discussion is still ongoing about the exact scope of the study, balancing the desire for a comprehensive report against the needs for answers to a few specific, targeted questions. We anticipate that this study will be commissioned by approximately the end of summer (September), and that a report will be delivered in Calendar Year 2014.

9. What is the process by which NSF incorporates peer review and opinions from the scientific community into their policies and strategic plans related to exoplanets?

A: Policies and strategic plans related to exoplanets are driven at a high level by National Research Council (NRC) studies, particularly the decadal survey in astronomy and astrophysics that was delivered in 2010. Priorities for large telescopes and for instrument development programs are derived directly from these surveys. Where the NRC studies must be extended to implementation issues, NSF Advisory Committees are used to advise on the strategy to implement the recommendations of such decadal surveys; the recent NSF Astronomy Portfolio Review is one major example of such an activity. When the NRC studies make particular recommendations regarding interagency strategies, such recommendations are discussed with the

Astronomy and Astrophysics Advisory Committee (AAAC). The AAAC annual report for 2013 in fact contained no recommendations specific to exoplanets, because there were no open questions of interagency strategy on exoplanets that were on the table in the last year.

At a micro-level, peer review from individual scientists is used to review research grant proposals on exoplanets, as well as the competitive instrumentation proposals related to exoplanets. Thus, although overall strategy may be set by the high-level community reports, the implementation of that strategy depends on the decisions made by the entire community of researchers via the competitive merit-review process. For example, many research groups may propose different technological approaches to improve the precision of radial velocity measurements needed to find Earth-mass planets, and the community assessment of individual research programs is the method that is used to fund the best of those ideas.

10. What are the differences between government-funded exoplanet research and exoplanet research in the private sector? Does each carry equal weight in the scientific community?

A: Some exoplanet research is funded by universities via their own faculty funding and observatories, and most significant private-sector research is funded in some way by the federal government. For example, there are exoplanet researchers working at aerospace companies or NASA contractors, but in most cases, the funding of their research can be traced ultimately to government funding to develop, build, or operate a particular telescope or science mission. Significant exoplanet research is carried out by employees of a few science museums, but those individuals often apply for (and receive) research funding from NSF and NASA that supports the conduct of their research. In a response to a previous question, "citizen science" research on exoplanets was discussed. This research typically relies on a data set supplied by the federal government, and possibly leveraged by federal or state funding, but the individual citizen scientists are not funded by the government and could be viewed as part of the private sector. In all of these variations, the scientific community relies on a peer-review process for grants and publications that assesses the validity of a scientific investigation or result rather than being concerned with the particular affiliation of an individual researcher.

11. Does NSF have an education and public outreach plan related to exoplanets?

A: NSF does not have a separate plan for exoplanet outreach, but it does have a requirement that every grant proposal address the "broader impacts" of the work to benefit society. Many investigators meet this requirement by carrying out an education or public outreach plan as part of their project, and these plans can include training students, working with K-12 teachers, "citizen science" projects, planetarium programs and many other activities.

Questions submitted by Rep. Donna Edwards

1. How can this Committee assess the effectiveness of the ground-based initiatives currently underway in addressing the scientific objectives identified in the 2010 Decadal Survey for detecting and characterizing exoplanets? In your opinion, how effective are those initiatives?

A:The ground-based initiatives to detect and characterize exoplanets have been very successful so far. However the real evaluation of the success of a scientific research program may take many years to decades. Looking back over the past 20 years, NSF-funded astronomers made the first detections of exoplanets and of multi-planet systems, while more recent NSF funding has used Kepler data to find possibly habitable planets and to characterize the frequency of rocky planets around stars in our Galaxy. Some of the large initiatives that require significant telescope and instrumentation development will take most of the present decade, if not beyond, to come to fruition. As an example, a measure of success would be found in whether the precision of radial velocity measurements continues to advance from 1 m/s toward 0.1 m/s over the present decade. If this technological advance continues, the discovery of planets with masses approaching that of Earth, around a variety of different stars, must ultimately follow.

NSF believes that the community prioritization process that is part of the decadal surveys is an essential process for setting well-understood priorities and strategies for the long run. Rather than continually asking questions about the most important scientific directions to take, a framework and long-term strategy are established for the entire US community. In fact, one important aspect of this process is often overlooked, namely that all individual astronomers are aware of the priorities and initiatives recommended by the decadal survey. The review of every exoplanet proposal submitted to the NSF is carried out by individuals who are aware of the community priorities, and who factor those priorities into their ranking of proposals. The system of funding for exoplanet science by the NSF is, therefore, a novel combination of top-down and bottom-up activities, and one of the jobs that the NSF program staff take very seriously is ensuring that this combination continues to work effectively.

2. The latest Astronomy & Astrophysics Advisory Committee annual report recommends that NSF, within its long range planning, should identify a path to support the Mid-Scale Innovations Program that was recommended as the second priority large ground-based program. What would be its contribution, if any, to exoplanet research?

A: The decadal survey report described eight mid-scale programs that were thought to be particularly worthy examples of candidates for funding via a Mid-Scale Innovations Program (MSIP). Two of those examples, next-generation adaptive optics systems and development of high-precision radial velocity spectrographs, are directly applicable to exoplanet research. (Details have been discussed extensively in response to questions from other Representatives.) NSF released an MSIP solicitation to the community this month, with preliminary proposals due later this year; that solicitation was a direct response to the committee recommendations referenced in the question. The ability to contribute to exoplanet research through the MSIP line will depend directly on how much funding is available for this program through the remainder of the decade.

3. Should the information being disseminated on discoveries of Earth-sized planets be enhanced so that the public recognizes the challenges of identifying the existence of Earth-like conditions on these planets? How can the public's interest be engaged on a sustained basis in an environment where repetitive "discovery" announcements could lead to diminished interest? If the discovery of Earth-like planets is likely the only item of interest to the public, what can be done to address such expectations?

A: This is a very interesting question that goes to the basic understanding of science by the general public and policymakers, and the reporting of science by the media, as well as the actions of researchers and institutions. The central issue is how much context the public needs in order to understand the true significance of a newly announced scientific finding, and where the responsibility for providing that context lies. At some level, the context is provided by the lifelong education of Americans, both in the classroom and by other less formal means. Many Americans deal with similar issues daily, every time they hear a report of a new medical study concluding that a particular food is or is not a contributor to chronic disease. In principle, yes, exoplanet researchers should be doing what they can to explain the context of their discoveries—not merely how the discovery is new, but how much it still leaves unanswered. However, individual researchers in all scientific communities, and headline writers for news media, are motivated to make far-reaching statements about the importance of individual discoveries, which cannot be micro-managed by the federal agencies.

As for addressing the public's expectations for discovery, again this goes to the basic understanding that the frontiers of science always involve incomplete and imperfect information. Consider the goal of achieving sufficiently good imaging and spectroscopy of exoplanets to enable scientists to deduce the compositions of their atmospheres and something about their surfaces. Ultimately, researchers hope to identify spectroscopic signatures of chemical compounds that are possible products of biological processes. But in every case there will be debate as to whether a given chemical signature actually comes from biological activity or just from some interesting and unexpected non-biological chemistry. (We note here that there is still debate about the cause of interesting chemical signatures detected by NASA's Viking lander on Mars, more than 35 years ago.) It is therefore very possible that humanity may live for many centuries with the possibility that certain planets harbor life, but without being able to know for sure.

Appendix II

Additional Material for the Record

NASA EXOPLANET MISSIONS GRAPHIC SUBMITTED BY DR. JOHN M. GRUNSFELD