ADVANCES IN THE SEARCH FOR LIFE

HEARING

BEFORE THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
HOUSE OF REPRESENTATIVES

ONE HUNDRED FIFTEENTH CONGRESS

FIRST SESSION

APRIL 26, 2017

Serial No. 115–11

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

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

U.S. GOVERNMENT PUBLISHING OFFICE

25–467PDF WASHINGTON : 2017

For sale by the Superintendent of Documents, U.S. Government Publishing Office
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April 26, 2017

ADVANCES IN THE SEARCH FOR LIFE

WEDNESDAY, APRIL 26, 2017

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

The Committee met, pursuant to call, at 10:08 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Lamar Smith [Chairman of the Committee] presiding.

LAMAR S. SMITH, Texas
CHAIRMAN

EDDIE BERNICE JOHNSON, Texas
RANKING MEMBER

Congress of the United States
House of Representatives

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
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Advances in the Search for Life

Wednesday, April 26, 2017
10:00 a.m.
2318 Rayburn House Office Building

Witnesses

Dr. Thomas Zurbuchen, Associate Administrator, Science Mission Directorate, National Aeronautics and Space Administration (NASA)

Dr. Adam Burgasser, Professor of Physics, University of California, San Diego and UCSD Center for Astrophysics and Space Science; Fulbright Scholar

Dr. James Kasting, Chair, Planning Committee, Workshop on the Search for Life Across Space and Time, National Academies of Science, Engineering, and Medicine, Evan Pugh Professor of Geosciences, Pennsylvania State University

Dr. Seth Shostak, Senior Astronomer, SETI Institute

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

Charter

TO:	Members, Committee on Science, Space, and Technology
FROM:	Majority Staff, Committee on Science, Space, and Technology
DATE:	April 26, 2017
SUBJECT:	Full Committee Hearing: "Advances in the Search for Life"

On Wednesday, April 26, 2017 at 10:00 a.m. in Room 2318 of the Rayburn House Office Building, the Committee on Science, Space, and Technology will hold a hearing titled, "Advances in the Search for Life."

Hearing Purpose

The NASA Transition Authorization Act of 2017 established "The search for life's origin, evolution, distribution, and future in the universe," as one of the national space program's objectives. The hearing will survey recent breakthroughs in a variety of fields that contribute to astrobiology, such as the continued discovery of exoplanets and research efforts to understand life's origin on Earth and in the lab.

Witnesses

- **Dr. Thomas Zurbuchen**, Associate Administrator, Science Mission Directorate, National Aeronautics and Space Administration (NASA)
- **Dr. Adam Burgasser**, Professor of Physics, University of California, San Diego and UCSD Center for Astrophysics and Space Science; Fulbright Scholar
- **Dr. James Kasting**, Chair, Planning Committee, Workshop on the Search for Life Across Space and Time, National Academies of Science, Engineering, and Medicine, Evan Pugh Professor of Geosciences, Pennsylvania State University
- **Dr. Seth Shostak**, Senior Astronomer, SETI Institute

Staff Contact

For questions related to the hearing, please contact Mr. Tom Hammond, Staff Director, Space Subcommittee, Dr. Michael Mineiro, Professional Staff Member, Space Subcommittee, or Ms. Sara Ratliff, Policy Assistant, Space Subcommittee, at 202-225-6371.

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

Without objection, the Chair is authorized to declare recesses of the Committee at any time.

Welcome to today's hearing titled "Advances in the Search for Life."

Before I recognize myself and the Ranking Member for an opening statement, let me explain that both Republican and Democratic caucuses are now meeting. For reasons you can imagine, those meetings are going long, and there is much discussion, which means that everybody here left their caucuses early, so I hope you will consider that to be a form of compliment. But we do expect more Members to come in in the future few minutes.

I'll recognize myself for an opening statement.

For centuries, humanity has wondered if life might exist elsewhere in the cosmos. Only in the last few decades have we been able to detect the existence of other worlds.

Twenty-five years ago, we didn't know that planets existed beyond our solar system. Today, we have confirmed the existence of over 3,400 exoplanets that orbit other suns. And we continue to make new discoveries.

Today we can observe planets that may harbor life. Earlier this month, scientists announced the first detection of an atmosphere around an Earth-like planet outside our solar system. This is a significant step towards being able to determine whether some form of life exists there.

Last week, scientists announced the discovery of another Earth-like exoplanet in the habitable zone of a star 40 light-years away—close by in cosmic terms. It is a prime target for future investigation.

Even within our own solar system, scientists have found intriguing possibilities of habitability. NASA recently announced the discovery of hydrogen gas in plumes shooting from the icy surface of Saturn's moon Enceladus.

Organisms on Earth use hydrogen in a process to create nutrients. Perhaps simple organisms living near the moon's hydrothermal vents could use a similar process.

Hopefully, NASA will find similar conditions when it sends a spacecraft to investigate Jupiter's moon Europa, where scientists have identified plume-like features.

The United States pioneered the field of astrobiology and continues to lead the world in this type of research. Since its beginning, NASA has searched for life beyond Earth and has conducted numerous scientific investigations.

Supported by NASA, the 2017 Astrobiology Science Conference is meeting this week in Mesa, Arizona. The theme of the conference is "Diverse Life and its Detection on Different Worlds."

The NASA Transition Authorization Act of 2017, which President Trump signed into law last month, ensures continued American leadership in astrobiology and the search for life. It establishes "the search for life's origin, evolution, distribution, and future in the universe" as a fundamental objective for NASA. To accomplish this, the bill directs NASA and the National Academies to develop an exoplanet exploration strategy and an astrobiology strategy.

The pursuit of evidence of life beyond our planet fascinates the American people. Programs like the James Webb Space Telescope and the Wide Field Infrared Survey Telescope, both of which the NASA Transition Authorization Act supports, will further advance our understanding of exoplanets and inspire the next generation of American explorers.

We do not just look at places where life might be. We are laying the groundwork to go there. The National Academies highly recommended a mission to Europa. The Europa Clipper mission will greatly aid NASA's search for signs of life on Jupiter's moon.

Private citizens, amateur astronomers, and non-government organizations also play an important role in our search for life. Private citizens and philanthropists fund organizations such as the SETI Institute, which searches for extraterrestrial intelligence. Citizen scientists conduct astronomical observations and analysis of vast astronomical data sets.

Earlier this month, news came of a mechanic who used NASA data to help discover a new exoplanet system. This is a great example of citizen scientists at work. We should support more contributions from citizen scientists. It enhances public engagement and helps encourage the next generation of young students to pursue careers in astronomy, astrophysics and astrobiology.

It is human nature to seek out the unknown and to discover more about the universe around us. Many Americans often gaze into the beauty of the night sky in awe. We rightfully wonder if there is life beyond our pale blue dot.

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

[The prepared statement of Chairman Smith follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
April 26, 2017

Media Contact: Kristina Baum
(202) 225-6371

Statement of Chairman Lamar Smith (R-Texas)
Advances in the Search for Life

Chairman Smith: For centuries, humanity has wondered if life might exist elsewhere in the cosmos. Only in the last few decades have we been able to detect the existence of other worlds.

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It is human nature to seek out the unknown and to discover more about the universe around us. Many Americans often gaze into the beauty of the night sky in awe. We rightfully wonder if there is life beyond our pale blue dot.

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

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Chairman SMITH. That concludes my opening statement, and the Ranking Member, the gentlewoman from Texas, Eddie Bernie Johnson, is recognized for hers.

Ms. JOHNSON. Thank you very much, Mr. Chairman, and good morning, and we welcome our witnesses.

Humanity's centuries-old quest to understand our place in the universe has gained significant ground in recent years. Geologists are uncovering evidence of the oldest life forms in Earth's geological record. The age of these fossils indicates that, as soon as conditions were right on Earth, life appeared. That discovery raises profound questions. Has the same thing occurred on other bodies within and beyond our solar system? Is the genesis of life a common occurrence throughout the universe?

Planetary scientists continue to find new environments within our solar system with the potential to harbor life. A key requirement for life as we know it is water and the mantra for the search for life beyond Earth has been to "follow the water." Recent discoveries indicate that our solar system has an abundance of it. NASA's Mars Reconnaissance Orbiter discovered intermittent flows of liquid water on or just below the Martian surface. The Hubble Space Telescope has sent back images of what appear to be intermittent water plumes gushing from the surface of Jupiter's moon, Europa. And the NASA Cassini mission has revealed evidence of hydrothermal activity in the subsurface water ocean of Saturn's moon, Enceladus. With indications of water on several other solar system bodies including asteroids and dwarf planets, and moons of Jupiter and Saturn, it appears that at least one condition for habitability is relatively common throughout our solar system.

How do recent discoveries of water and habitable environments in our own solar system inform the search for life on planets orbiting other stars? NASA's Kepler mission has more than doubled the number of known exoplanets, bringing astronomers closer to finding an elusive Earth twin. The upcoming launch of the James Webb Space Telescope and the Transiting Exoplanets Survey Telescope will provide more opportunities to study these systems and to uncover new ones.

There appear to be many possible environments to search for life, both within our solar system and beyond. To narrow down the targets for research and exploration, scientists are working to understand fully how life originated here on Earth.

The study of Earth's history, the early forms of life on Earth, and how the two evolved together is critical to this effort. And so, the search for life truly is an interdisciplinary endeavor that draws on expertise in core science disciplines like biology, geology, chemistry, physics, and astronomy. The strength of these core disciplines is central to making maximum progress in the search for life beyond Earth, and that's why we need to be committed to keeping America's research enterprise strong. We need to continue to invest as a Nation in research and development, not cut back.

I feel fortunate to be serving on the Science Committee at a time when progress is being made so rapidly in the search for life beyond Earth, and I look forward to hearing about that progress from our witnesses.

With that, I yield back, Mr. Chairman.

[The prepared statement of Ms. Johnson follows:]

OPENING STATEMENT
Ranking Member Eddie Bernice Johnson (D-TX)

House Committee on Science, Space, and Technology
"Advances in the Search for Life"
April 26, 2017

Good morning, and welcome to our witnesses.

Humanity's centuries-old quest to understand our place in the universe has gained significant ground in recent years. Geologists are uncovering evidence of the oldest life forms in Earth's geological record. The age of these fossils indicates that, as soon as conditions were right on Earth, life appeared. That discovery raises profound questions. Has the same thing occurred on other bodies within and beyond our solar system? Is the genesis of life a common occurrence throughout the universe?

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I feel fortunate to be serving on the Science Committee at a time when progress is being made so rapidly in the search for life beyond Earth and I look forward to hearing about that progress from our witnesses. With that, I yield back.

Chairman SMITH. Thank you, Ms. Johnson.

And the Chairman of the Space Subcommittee, the gentleman from Texas, Mr. Babin, is recognized for his opening statement.

Mr. BABIN. Thank you, Mr. Chairman. Great to see everybody. Thanks for being here.

The science of astronomy, astrophysics and astrobiology expands mankind's understanding of our universe. It seeks to answer fundamental questions as to the nature of our Universe, our place within it, and whether there is life beyond Earth.

NASA has a long history of space-based astrophysics and astronomical science. Since the 1960s, NASA has operated space-based observatories. Among the most famous of these are the Hubble Space Telescope, which has produced some of the clearest images of the Universe to date.

Looking to the future, the James Webb Space Telescope, or JWST, set to launch in 2018, will be the most powerful space-based observatory to date and will be used to search for planets outside our solar system that could harbor life.

In my own district, at Johnson Space Center in Houston, NASA's historic Chamber A thermal vacuum testing chamber is being used for end-to-end optical testing of JWST in a simulated cryo-temperature and vacuum space environment. I'm proud to represent the hardworking men and women at Johnson Space Center contributing to JWST, our Nation's next great space-based observatory.

Johnson Space Center is also home to NASA's Astromaterials and Curation Office. This office is responsible for the curation of extraterrestrial samples from NASA's past and future sample return—from future return missions. This is an exciting responsibility for Johnson Space Center and an important contribution in the search for life beyond Earth.

We live in exciting times. The NASA Authorization Act of 2017 provides strong direction for NASA to continue to search for life and advance the science of astronomy, astrophysics and astrobiology. It is quite possible that with continued efforts, humanity will finally answer the question and know definitely whether life exists on other worlds.

I thank today's witnesses for joining us today and I look forward to hearing your testimony, and I yield back, Mr. Chairman.

[The prepared statement of Mr. Babin follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
April 26, 2017

Media Contact: Kristina Baum
(202) 225-6371

Statement of Space Subcommittee Chairman Brian Babin (R-Texas)
Advances in the Search for Life

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I thank today's witnesses for joining us today and I look forward to hearing your testimony.

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Chairman SMITH. Thank you, Mr. Babin.

And the gentleman from California, Mr. Bera, the Ranking Member of the Space Subcommittee, is recognized for an opening statement.

Mr. BERA. Thank you, Mr. Chairman, and thank you for holding this hearing on the Advances in the Search for Life. That is a timeless question, the question "Are we alone?"

Over the centuries, whether it's the child lying on the grass looking up at the vastness of our universe to the most advanced astrophysicist thinking about this question, and that is exactly what we ought to be doing as a species—asking those questions. We're curious by nature. We're explorers. And if you think about what we're discovering and what we have discovered in recent years from the deep oceans on the moons of Enceladus and Europa, to the surface of Mars, the rapidity of findings habitable planets, you know, vastly moves us forward to answering that question: "Are we alone?"

Now, what we may discover is not necessarily species that look like us but what we may discover are the building blocks of life, looking for water, looking for organic molecules, looking for bacteria.

But when that happens, and inevitably that discover will likely happen in our lifetimes, the disruption that answers that question of are we alone is remarkable. I mean, if you think about 1997 with the Cassini space mission, we didn't know what we were going to discover, and yet, you know, we're seeing plumes of spewing material from Enceladus, let alone flying through those plumes and discovering what we may discover.

So we live in this remarkable time. The Chairman of the Space Subcommittee talked about the advances and discoveries of Hubble and Hubble's sibling that will launch shortly, James Webb, what that's going to allow us to discover about who we are, where we are, and where we go from here. You know, again, this is a remarkable time.

You know, the energy we saw this past weekend with thousands if not hundreds of thousands of folks marching around the country in support of science, around the world, in fact, these are discoveries that are not just unique to who we are as the United States but to who we are as humanity, and again, you know, I am encouraged by the Chairman and the President's budget of the support for NASA funding and the support for continuing to explore and look for that next discovery. You know, this is incredibly important. At the same time as we make those discoveries, it helps us better understand who we are as a planet on Earth, how we evolved and where we may go next.

So as we move forward, as we start looking at NASA's 2018 budget, you know, let's make sure we continue to find that exploration externally but we also understand NASA's multi-mission role here on Earth as well, that we continue to encourage, you know, the basic investments in basic science research in astrobiology and that search for life, and again, that we understand as we're going through the 2018 budget debate that we understand the impacts of cutting budgets and we continue to support NASA's multiple role.

So, you know, I think this is a great time for this hearing. This is an exciting time in that search for an answer to the question "Are we alone?"

And with that, I yield back.

[The prepared statement of Mr. Bera follows:]

OPENING STATEMENT
Ranking Member Ami Bera (D-CA)
of the Subcommittee on Space

House Committee on Science, Space, and Technology
"Advances in the Search for Life"
April 26, 2017

Good morning and welcome to our distinguished panel of witnesses. Thank you, Mr. Chairman, for holding this hearing on *"Advances in the Search for Life"*.

Based on years of investigations across NASA's science portfolio, researchers are increasingly finding evidence of life's basic building blocks– liquid water, organic molecules, minerals, and a source of energy - occurring beyond Earth.

From the deep oceans on the moons Enceladus and Europa, to the surface of Mars, and possibly planets and planetary systems now being identified beyond our solar system, the list of potentially habitable locations for life in the Universe continues to grow.

I look forward to hearing from our witnesses on highlighting the many compelling findings about these and other advances in the search for life beyond Earth.

This abundance of scientific discovery is just one example of the return on our nation's investments in basic research within NASA's science portfolio and across the Federal government.

No one imagined that when the Cassini/Huygens mission was launched in 1997 to study Saturn and its moons, it would wind up identifying plumes spewing material from Enceladus, or let alone flying through the plumes and detect the elements needed to support potential life.

And no one could have known about the diverse environment that exists on Mars without the systematic investigation of the planet by orbiting spacecraft, landers, and rovers over several decades.

Our understanding of Earth and its capacity to support life - its origins, evolution, and its ability to survive in extreme environments – strongly inform the search for life beyond Earth and wouldn't be possible without our investments in basic scientific research including chemistry, biology, geology, and physics.

The discoveries of today are the result of our past investments in research. Robust investments now and into the future will shape the story our children and grandchildren tell 20 or 30 years from now about Earth, our solar system, and perhaps even the existence of life beyond planet Earth.

However, that story will partially depend on advances that we make in research and technology across NASA's mission areas, including telescopes, instruments, spacecraft and the other systems needed to investigate potentially habitable locations across our universe.

And while today's search for life relies solely on robotic missions, NASA's Journey to Mars program offers the pathway for humans to one day contribute to the study of whether Mars supports or once supported life.

So, as we consider the details of the President's Fiscal Year 2018 budget proposal that are expected next month, I urge all of us to consider:

- the importance of NASA's multi-mission role in the search for life beyond Earth,
- the relationship of investments in basic science research to the multidisciplinary study of astrobiology and the search for life, and
- the impact of potential budget cuts on extended missions such as the one that led to Cassini's recent scientific discoveries.

Thank you and I yield back.

Mr. MCNERNEY. Will the gentleman yield?

Mr. BERA. Sure, I'll yield.

Mr. MCNERNEY. I just want to thank the Chairman for this hearing.

This is an exciting hearing, but the only definitive answer possible is the affirmative. We can never answer definitively that there's no life outside of the Earth. So that's one of our challenges, but nothing has the ability to capture the imagination, the enthusiasm of people that the possibility of extraterrestrial life. So you all have the ability to really capture the American people's imagination and attention, and we need that now. We need people to be enthusiastic about science, so my hat's off to you, and I encourage you to do the best you can.

With that, I yield back.

Chairman SMITH. Thank you, Mr. Bera.

Let me introduce our panelists, and let me just say ahead of time that our hearings are always this bipartisan. You're the happy recipients of not only great attendance but great interest as well.

Our first witness today is Dr. Thomas Zurbuchen, Associate Administrator of the Science Mission Directorate at NASA. Dr. Zurbuchen previously served as a Professor of Space Science and Aerospace Engineering at the University of Michigan. He has worked on several NASA science missions including Ulysses, the MESSENGER spacecraft to Mercury, and the Advanced Composition Explorer. He earned both his master's of science degree and his Ph.D. in physics from the University of Bern in Switzerland.

Our second witness today is Dr. Adam Burgasser, Professor of Physics at the University of California in San Diego. Dr. Burgasser was awarded a 2017–18 Fulbright Scholarship to conduct astrophysical research in works with University of California-San Diego Center for Astrophysics and Space Science. He contributed to the discovery of the TRAPPIST–1 system and currently conducts research in physics. He specifically investigates the lowest mass stars, coldest brown dwarves, and exoplanets. He earned his bachelor's of science in physics at the University of California-San Diego and his Ph.D. in physics from the California Institute of Technology.

Our third witness today is Dr. James Kasting, Chair of the Planning Committee of the Workshop on the Search for Life Across Space and Time at the National Academies of Science, Engineering and Medicine. He also is an Evan Pugh Professor of Geosciences at Pennsylvania State University. He spent two years at the National Center for Atmospheric Research and seven years in the Space Science Division at the NASA Ames Research Center. Dr. Kasting also chaired NASA's Exoplanet Exploration Program Analysis Group from 2009 to 2011. He earned his undergraduate degree in chemistry and physics from Harvard University and his Ph.D. in atmospheric sciences from the University of Michigan.

Our fourth witness today is Dr. Seth Shostak, Senior Astronomer at the SETI Institute. For ten years, Dr. Shostak chaired the International Academy of Astronautics SETI Permanent Committee. Dr. Shostak has written, edited, and contributed to a half-dozen books on the search for life. His most recent work, Confessions of an Alien Hunter, details the history and scientific methodology of

SETI. Dr. Shostak gives approximately 60 presentations annually and is the regular host of the SETI Institute's weekly 1-hour science radio show, Big Picture Science. Dr. Shostak earned an undergraduate degree in physics from Princeton University and a doctorate in astronomy from the California Institute of Technology.

We welcome you all, and Dr. Zurbuchen, if you will begin?

TESTIMONY OF DR. THOMAS ZURBUCHEN, ASSOCIATE ADMINISTRATOR, SCIENCE MISSION DIRECTORATE, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA)

Dr. ZURBUCHEN. I'd be glad to. Mr. Chairman and Members of the Committee, this is an exciting time for exploration and discovery, and especially the search for life elsewhere, and I'd like to begin by expressing our gratitude for the Committee's long-term support of our efforts in this area. In particular, we are pleased by the Committee's inclusion of a provision in the recently passed Authorization Act that makes astrobiology and the search for life part of NASA's mission. We are not only committed but also enthusiastic about accomplishing the objectives that the Congress and the President have laid out for us. Furthermore, NASA is initiating work with the National Academies to develop science strategies for astrobiology and the study of exoplanets as requested.

As part of our astrobiology effort, NASA supports research that leads to a better understanding of how life emerged and evolved on Earth, what conditions make any environment in our universe capable of harboring life, and what is the potential distribution of such worlds are with life beyond Earth. To fully engage in this pursuit, we need a convergence of many fields—biology, geology, astronomy, planetary sciences, Earth sciences, and many other disciplines. Together these researchers from these fields are exploring one of the greatest questions of our times. For example, just two weeks ago, NASA's Cassini Mission confirmed the presence of hydrogen from plumes of Saturn's moon Enceladus while our Hubble team announced the second observations of possible plumes on Jupiter's moon Europa. Both discoveries displayed a potential of life-enabling energy sources in oceans hidden away from our view beyond the icy crust and a confirmation which will be very significant for this science. That's because scientists believe the plumes are spewing from cracks of these moons icy shells with material that are indicative of hydrothermal activity in their ocean floors, and we know from Earth that those parts of our world are spaces with lots of life, and while we haven't found definitive signs of life elsewhere just yet, our search is making remarkable progress, and astrobiology is the focus of a growing number of NASA missions.

Mars 2020, our next rover after Curiosity, will continue to advance this search by investigating a region of Mars where the ancient environment may have been favorable to microbial life. Science instruments on the rover will provide high-resolution imaging and spectroscopy in many ways for characterizing rocks and soil from a distance. The Mars 2020 mission will also search for signs of past life, and throughout its investigation will collect samples that we hopefully can return in the future back to Earth to the best labs we have.

NASA is currently developing a Europa Clipper Mission, which will conduct a detailed reconnaissance of Europa and investigate whether the icy moon could harbor conditions suitable for life. The promise of Europa Clipper is increasing day to day. If the potential plumes are linked to the subsurface oceans, studying their composition would help scientists investigate the chemical makeup of Europa's potentially habitable environment while minimizing the need to drill through layers of ice.

Beyond our solar system, a transformation of understanding is taking place regarding planets around other stars—exoplanets. I was in grad school when the first planet orbiting another star was announced. I still remember it vividly the day, the moment when I learned about this. It was so exciting, and that was just the beginning of an avalanche of discoveries. You mentioned we have close to three and a half thousand of such planets found and discovered elsewhere and billions more are waiting to be revealed in our galaxy alone.

This February, NASA's Spitzer Space Telescope team announced the discovery of seven Earth-sized planets, the most ever found around a single star, TRAPPIST–1, and I'll leave up to you, Dr. Burgasser, to kind of fill in the details. It's really exciting, and discoveries are coming out by the day on this one.

NASA's Spitzer, Hubble and Kepler space telescopes will continue to help astronomers plan for such follow-up studies using NASA's upcoming James Webb Telescope launching in 2018. With much greater sensitivity, Webb will be able to detect the chemical fingerprints of water, methane, organics, other important molecules that really are related, we believe, to life and the factor that help us assess whether these worlds have an ability to harbor life.

With all this activity related to the search of life in so many different areas, we are on the verge of one of the most profound discoveries ever. Thank you.

[The prepared statement of Dr. Zurbuchen follows:]

Statement of

Dr. Thomas Zurbuchen
Associate Administrator
Science Mission Directorate
National Aeronautics and Space Administration

before the

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

Mr. Chairman and Members of the Committee, thank you for the opportunity to appear today to discuss the topic of astrobiology. As you all know, this is an exciting time for space exploration and discovery, and especially the search for life elsewhere, and I would like to begin by expressing our gratitude for the Committee's long-term support of our efforts in this area.

In particular, we are pleased by the Committee's inclusion of a provision in the recently passed NASA Transition Authorization Act of 2017 that expressly makes astrobiology and the search for life part of NASA's core statutory mission. We are not only committed to but also enthusiastic about accomplishing the objectives that Congress and the President have laid out for us. Furthermore, NASA is initiating work with the National Academies to develop science strategies for astrobiology and the study of exoplanets as requested by the 2017 Authorization Act. Once complete, these strategies will be used in planning and funding research and other activities as well as to provide a foundation for future initiatives related to astrobiology and exoplanet research.

I have been working in NASA's Science Mission Directorate (SMD) for about seven months now and have come to appreciate the shear breadth and depth of our mission portfolio. And while most often, we think about our missions in terms of the science area in which it is managed, such as Astrophysics or Planetary Science, I find it useful to think about these missions in terms of how they contribute to three themes that are central to everything we do.

The first of these themes is that we seek to expand knowledge – by investing in fundamental research to increase what we know and enlarge the space in which we live. Secondly, SMD is working with the greater scientific community on a focused science objective to search for life elsewhere, our second theme, which we will highlight today. The third theme is safeguarding and improving life on Earth, which refers to the research and missions from many disciplines that directly affects people on the ground, including Earth science, space weather and planetary defense. We are excited and inspired when SMD's fundamental research has direct and positive impacts in our lives!

As part of our astrobiology effort, NASA supports research that leads to a better understanding of how life emerged and evolved on Earth, what conditions make any environment in our universe capable of supporting life, and what is the potential distribution of habitable worlds and life itself beyond Earth. Searching for life elsewhere is a collaborative and interdisciplinary theme by necessity. To fully engage in this pursuit, we need a convergence of the areas of biology, heliophysics, Earth science, astronomy, planetary science, and the astrophysical search for Earth-like planets that might show signs of life. Together, researchers in these fields are exploring one of the greatest questions of our time.

For example, just two weeks ago, NASA's Cassini mission confirmed the presence of hydrogen from plumes on Saturn's moon Enceladus while our Hubble Space Telescope team announced the second observation of possible plumes near the equator of Jupiter's moon Europa. Both discoveries display the potential for life-enabling energy sources in oceans hidden from view under an icy crest, a confirmation of which would be significant to all of NASA. That's because scientists believe the plumes are spewing from cracks in these moons' icy shells with material indicative of hydrothermal activity on their ocean floor; and we know that within many hydrothermal vents in our deep oceans on Earth, we find life. Scientists are currently debating if life may have originated at locations like these.

And while we haven't found definitive signs of life elsewhere just yet, our search is making remarkable progress and astrobiology is a focus of a growing number of NASA missions.

One such mission is NASA's *Curiosity* rover, which has found evidence that ancient Mars did have the right chemistry to have supported microbial life as well as evidence that the raw ingredients for life to get started existed on the red planet at one time. Since landing in 2012, the rover has also found evidence of an ancient streambed and just last year, found chemicals in rocks that suggest Mars once had more oxygen in its atmosphere than it does now, indicative of a disequilibrium that also points to an environment supportive of past life.

Mars 2020, our next rover currently in development, will continue to advance this search by investigating a region of Mars where the ancient environment may have been favorable for microbial life. On the rover's mast, two science instruments will provide high-resolution imaging and three types of spectroscopy for characterizing rocks and soil from a distance, also helping to determine which rock targets to explore up close. Two science instruments mounted on the Mars 2020 rover's robotic arm will be used to search for signs of past life and determine where to collect samples by analyzing the chemical, mineral, physical and organic characteristics of Martian rocks. Throughout its investigation, it will collect samples of soil and rock, and cache them on the surface for potential return to Earth by a future mission. Given the sophisticated instrumentation available on Earth, returned samples could provide the biggest leap forward in understanding the biological potential of Mars. NASA is exploring a range of possible ways to potentially return these cached samples to Earth, including a future NASA Science or NASA-sponsored mission, or via a commercial or international partnership. We are exploring opportunities to partner with industry to leverage their future missions to advance decadal survey science objectives.

Beyond Mars, we focus on the ocean worlds of our outer solar system. A particularly interesting destination is Jupiter's moon Europa - which appears to meet the minimum requirements for life. Thus, NASA is currently developing a Europa *Clipper* mission, which will conduct a detailed reconnaissance of Europa and investigate whether the icy moon could harbor conditions suitable for life. The mission's nine science instruments include cameras and spectrometers to produce high-resolution images of Europa's surface and determine its composition. An ice penetrating radar would determine the thickness of the moon's icy shell and search for subsurface lakes similar to those beneath Antarctica's ice sheet.

The mission would also carry a magnetometer to measure the strength and direction of the moon's magnetic field, which would allow scientists to determine the depth and salinity of its ocean. Finally, a thermal instrument would survey Europa's frozen surface in search of recent eruptions of warmer water at or near the surface, while additional instruments would search for evidence of water and tiny particles in the moon's thin atmosphere.

The promise of Europa Clipper is increasing: As previously mentioned, NASA's Hubble Space Telescope has recently observed collimated water vapor near Europa's equator multiple times, providing evidence of water plumes. If the plumes are linked to a subsurface ocean, studying their composition would help scientists investigate the chemical makeup of Europa's potentially habitable environment while minimizing the need to drill through layers of ice.

Beyond our solar system, a transformation of understanding is taking place regarding planets around other stars, or exoplanets, by means of NASA missions. To me, this tantalizing set of science discoveries is woven into my personal story.

I grew up in a small farm town in the Swiss mountains, one of the most beautiful places on Earth. By day I would explore the snowcapped mountains and crystal blue lakes, and by night the brilliant stars would transfix me with their beauty and seemingly endless number, sitting on the roof of our house with a star-map. How many of them were there, I wondered? I read books in the library and began learning more and more about the sheer magnitude of the universe, the peculiar objects that were in there, like exploding stars, black holes, neutron stars and speculation about worlds around other stars, possibly worlds just like ours.

I was in graduate school when the first planet orbiting a "normal" star other than our own was announced by a team of Swiss astronomers. This planet, 51 Pegasi b, was large like Jupiter (half the mass), but orbited closer to its star than Mercury does to our Sun, speeding through its entire orbit in only four days. To say that this discovery was a surprise is a huge understatement – no one thought that giant planets could exist in such close proximity to a star. This discovery was met with skepticism – but within a few months it was confirmed by a U.S. team using the Lick Observatory in California and a new field of astronomy was born. Now, with NASA missions like the Kepler and Spitzer Space Telescopes, we have discovered more than 3,400 exoplanets, with billions more just waiting to be revealed in our galaxy alone.

This February, NASA's Spitzer Space Telescope team announced the discovery of seven Earth-sized planets, the most ever, found around a single star, called TRAPPIST-1. Three of these planets are firmly located in the habitable zone, the area around the parent star where a rocky planet is most likely to have liquid water. This system of seven rocky worlds – all of them with the potential for water, a key to life as we know it – is an exciting discovery in the search for life on other worlds. The TRAPPIST-1 system is just 39 light years away and its discovery tells us that there is plenty of planet making material in our little corner of the solar system, indicating that finding Earth-like planets may actually be closer to us than we originally thought. Future study of this planetary system could reveal conditions suitable for life. Since the initial observations, the follow-on findings for TRAPPIST-1 (and exoplanets in general) are occurring almost weekly, but the best is yet to come.

NASA's Spitzer, Hubble, and Kepler Space Telescopes will continue to help astronomers plan for such follow-up studies using NASA's upcoming James Webb Space Telescope, launching in 2018. With much greater sensitivity, Webb will be able to detect the chemical fingerprints of water, methane, oxygen, ozone, and other components of a planet's atmosphere. Webb also will analyze planets' temperatures and surface pressures – key factors in assessing their habitability.

The Transiting Exoplanet Survey Satellite (TESS) mission will also launch next year, to survey the entire sky for nearby exoplanets, and the Wide Field Infrared Survey Telescope (WFIRST), launching in the mid-2020s, will directly image exoplanets and study their atmospheric chemistry for the first time using reflected light from their stars. NASA is studying mission concepts even beyond these near-term missions for the 2030s that would further explore and characterize the bounty of possible habitable Earth-like planets. These mission concepts include the Habitable Exoplanet Imaging Mission and the Large Ultraviolet/Visible/Infrared Surveyor, which would operate from the ultra-violet to the near-infrared like Hubble and WFIRST, and the Origins Space Telescope, which would operate from the mid-infrared to the far infrared like the James Webb telescope.

With all of this activity related to the search for life, in so many different areas, we are on the verge of one of the most profound discoveries, ever. And as we know from experience, NASA's scientific discoveries of today continually drive impactful research for tomorrow that goes far beyond the initial observations.

For astrobiology, the key thing to remember is that answering the fundamental question of "is there life out there?" will require scientific breakthroughs from many different science fields, including ones that are not currently engaged in this exciting endeavor. This, however, demonstrates the nature of great research: it's not just about answering questions that have been asked in the past, it is about finding entirely new questions that will have impact for a long time to come.

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

Dr. Thomas Zurbuchen is the Associate Administrator for the Science Mission Directorate at the Agency's Headquarters in Washington, D.C.

Previously, Zurbuchen was a professor of space science and aerospace engineering at the University of Michigan in Ann Arbor. He was also was the university's founding director of the Center for Entrepreneurship in the College of Engineering. Zurbuchen's experience includes research in solar and heliospheric physics, experimental space research, space systems, and innovation and entrepreneurship.

During his career, Zurbuchen has authored or coauthored more than 200 articles in refereed journals on solar and heliospheric phenomena. He has been involved with several NASA science missions -- Ulysses, the MESSENGER spacecraft to Mercury, and the Advanced Composition Explorer (ACE). He also has been part of two National Academy standing committees, as well as various science and technology definition teams for new NASA missions.

Zurbuchen earned his Ph.D. in physics and master of science degree in physics from the University of Bern in Switzerland.

His honors include receiving the National Science and Technology Council Presidential Early Career for Scientists and Engineers (PECASE) Award in 2004, a NASA Group Achievement Award for the agency's Ulysses mission in 2006, and the Swiss National Science Foundation's Young Researcher Award in 1996-1997.

Chairman SMITH. Thank you, Dr. Zurbuchen.
And Dr. Burgasser.

TESTIMONY OF DR. ADAM BURGASSER, PROFESSOR OF PHYSICS, UNIVERSITY OF CALIFORNIA, SAN DIEGO AND UCSD CENTER FOR ASTROPHYSICS AND SPACE SCIENCE; FULBRIGHT SCHOLAR

Dr. BURGASSER. Thank you, Chairman Smith, Ranking Member Johnson, and esteemed Members of the Committee. It is an honor to share with you today recent discoveries and future opportunities in the search for potentially habitable worlds and life amongst the smallest stars.

I speak today as a representative of the international team that discovered the seven-planet system around the star TRAPPIST–1, a system that harbors as many as three potentially habitable Earth-size worlds. This and other recent discoveries represent the beginning of an era of exoplanet exploration that in the next 5 to ten years will allow us to identify truly habitable worlds and possibly life beyond Earth. These transformative advances addressing one of humanity's most persistent questions—are we alone?—are fully achievable through a diverse portfolio of research programs led by U.S. scientists and supported by federal funding to NASA, NSF and other science agencies. Slide, please.

[Slide.]

Today I will focus my testimony on the opportunities afforded by the lowest mass stars. When we look up in a clear night sky, most of the stars we see are hot, massive and distant. This visual sample does not reflect our Milky Way galaxy's actual stellar population, which is dominated by cool, low-mass and dim stars barely perceptible, even with the largest telescopes. Next slide, please.

[Slide.]

These low-mass stars outnumber sun-like stars five to one and include some of our nearest stellar neighbors, many discovered just in the past five to ten years, thanks to deployment of advanced infrared detector technology and missions such as NASA's Wide field Infrared Survey Explorer.

The search for potentially habitable worlds around these scars is a search for terrestrial planets with surfaces on which liquid water can persist. Such planets reside in the Goldilocks habitable zones around stars—not too hot, not too cold. For low-mass stars, this habitable zone can be up to 20 times closer to the star than Earth is to the sun, which makes such planets easier to find and easier to study. Next slide, please.

[Slide.]

Thanks to public investment in technology, facilities and people, this search has borne fruits. In 2014, the NASA Kepler spacecraft team reported discovery of Kepler-185F, the first Earth-size world in the habitable zone of another star, work led by my former classmate and San Diego native, Dr. Lisa Quintana, now at NASA Goddard.

Just last year, it was announced that the nearest star to our sun, Proxima Centauri, has a super-Earth planet orbiting its habitable zone. Next slide, please.

[Slide.]

The University of Puerto Rico at Arecibo's Planet Habitability Lab tabulates 12 very likely habitable worlds identified to date, all of which orbit stars less massive than the sun. Next slide, please.

[Slide.]

The discovery of the TRAPPIST–1 system is a capstone to this endeavor and an example of how partnerships between universities, government agencies, and international collaborators can produce truly transformative results. TRAPPIST stands for the Transiting Planets and Planeteslmals Small Telescope, a facility operated by the University of Liege, Belgium, and led my colleague, Dr. Michael Gillon. I should say TRAPPIST is also the name of a popular Belgian beer.

This facility is relatively modest: a robotic telescope with a 2-foot-wide mirror optimized for the search of planets around the lowest mass stars. Even the stars are modest. TRAPPIST–1 is only eight percent the mass of the sun and is about the size of Jupiter, yet our international team, which includes scientists, students, and engineers from two dozen institutions and 11 countries on five continents including U.S. researchers in the states of California, Maryland, Massachusetts, Texas, and Washington were able to mobilize our shared resources to make this exciting discovery. Next slide, please.

[Slide.]

Key to our success was NASA's Spitzer Space Telescope, America's flagship infrared space facility, that monitored TRAPPIST–1 for 21 days, revealing this amazing light curve. Each dip you see is one or more of the planets passing between the star and us, dimming the starlight by less than one percent. We detected 92 transits associated with seven planets, all around the size of the Earth, with orbital periods between 1–1/2 and 18.8 days. The planets in this compact system fit easily within the orbit of Mercury and are so close that they gravitationally tug each other, causing measurable variations in their transit times. Such a compact system would be cooked if it was in our solar system but around a cool star like TRAPPIST–1, three of the planets, E, F and G, orbit within the star's habitable zone.

With three changes for a habitable world, the TRAPPIST–1 system is one of the most promising to date in the search for life beyond the solar system, but all indications are that this is just the tip of the iceberg.

Chairman Smith mentioned the discovery around—of a super Earth around the habitable zone of a nearby star by the NSF-funded MEarth project, and this will be joined by a space-based project TESS in the next year that we expect will discover hundreds of stars around other planets.

Our generation is the first in human history to know that there are worlds beyond our solar system. Will the next generation know whether life exists on those worlds? We have the opportunity and responsibility to continue our Nation's legacy of exploration discovery so that our children and grandchildren can search for life in new ways.

[The prepared statement of Dr. Burgasser follows:]

New Opportunities in the Search for Life Among the Lowest-Mass Stars

Statement of

Dr. Adam Jonathan Burgasser
Professor, University of California, San Diego
Department of Physics
Center for Astrophysics & Space Sciences

before the

Committee on Science, Space, and Technology,
United States House of Representatives 115th United States Congress

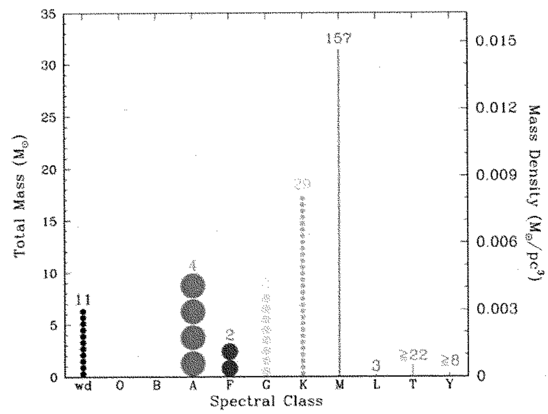
On

Advances in the Search for Life

April 26, 2017

Chairman Smith, Ranking Member Johnson, and esteemed Members of the Committee, it is an honor and privilege to discuss with you recent discoveries and future opportunities in the search for potentially habitable worlds and life among the smallest stars. I am particularly honored to speak today as a representative of the team that discovered the seven-planet system around the star TRAPPIST-1, a system that harbors as many as three potentially habitable Earth-sized worlds. This and other recent discoveries represent a beginning of an era of exoplanet exploration that in the next 5-10 years will enable measurements that identify habitable worlds and possibly life beyond Earth. In the next 15-25 years, we will have the capability to directly image other Earths. These transformative discoveries, which address one of humanity's most persistent questions, "Are We Alone?", are fully achievable through a diverse portfolio of research programs led by US scientists and supported by federal funding to NASA and NSF.

My own research interests center on cool, low-mass stars like TRAPPIST-1, which are the most common stars in the Milky Way Galaxy, and yet in many ways the most difficult to study. My path to this work began as a child in the late 1970s and 1980s in post-industrial Buffalo, NY, at a time when Dr. Carl Sagan appeared on PBS to talk about the beauty of the billions of galaxies, stars and worlds in the cosmos; and when the Voyager 2 spacecraft sent back the first close-up views of Uranus and Neptune. My love of math fed an interest in physics and a deep curiosity about the Universe, encouraged by many teachers and mentors. As an undergraduate and Physics major at UC San Diego, I had the privilege to work with Dr. Sally Ride on a project, which enabled high school students around the country to take pictures of their own planet. As a PhD student at Caltech, I used data from the 2 Micron All Sky Survey (2MASS), a sky



(Figure 1) The distribution of stars within 25 light-years of the Sun, ordered by spectral type. Massive hot stars are to the left, low-mass cool stars are to the right. The Sun is one of 8 G-type stars in the local volume. The vast majority of stars are dim, low-mass M dwarfs. (From Kirkpatrick et al. 2012, *Astrophysical Journal* **753**, 156)

survey using newly developed infrared array technology, to discover an entire class of invisible, low-mass stars. These data were available to myself and many other early career scientists exploring new areas of astronomical research thanks to federal funding provided by NASA and NSF. Today, I am able to weave these life-long scientific interests into the search for potentially habitable worlds around the lowest mass stars, a search that has recently born fruit and is transforming the way we see the Universe and our place within it.

Overview

When we look up into a clear, dark night sky, most of the stars we see are hot, luminous, massive and distant. This "visible" sample is not representative of our Milky Way's overall stellar population, which is dominated by cool, low mass and dim stars, barely perceptible even with a sizeable telescope. Astronomers designate these stars as cool or ultracool dwarfs. Compared to our Sun they are less than half as warm, have less than half the mass, and radiate less than 1% of the light energy. Most of this light is emitted at far-red visible and infrared wavelengths, beyond our visual range. They are literally invisible stars, only recently discovered in large numbers thanks to infrared detector technology development (a collaboration of military, university and private research) and the use of these detectors in federally supported surveys of the sky. Despite their recent detection, these lowest-mass stars are proving to be extremely important in the search for life in our Universe.

Cool dwarf stars have a number of unique properties that are important in the search for life beyond our Solar System. First, they are common. Over 75% of stars in the immediate vicinity of the Sun are cool or ultracool dwarfs (Figure 1), and the lowest-mass stars (≤10% the mass of the Sun) are more than five times more abundant that Sun-like stars. This fact means that low-mass stars are typically the closest stars to the Sun, including the closest star, Proxima Centauri (12% of the Sun's mass), 4.2 light-years away. The 5th, 6th and 7th nearest stars to the Sun, and a star that passed within 1 light-year of the Sun roughly 70,000 years ago, are examples of very low-mass stars found only the past 4 years. These stars have extremely long lifetimes, measured as the time over which they extract energy from the fusion of hydrogen into helium in their hot cores. The Sun is about halfway through its lifetime and will deplete its core hydrogen supply in the next 4-5 billion years (in the process, engulfing or rendering uninhabitable the inner terrestrial planets). The lowest-mass stars will continue to fuse hydrogen for *trillions* of years, one hundred times longer than the current age of the Universe. This means that nearly every low-mass star ever formed is still around today and will persist well past the demise of the Sun, making them very long-term sanctuaries for life if they possess habitable worlds. Finally, we now know that the lowest-mass stars are capable of forming planets - and specifically Earth-sized planets – thanks to recent discoveries summarized in this testimony.

Why search for habitable worlds around the lowest-mass stars?

The low-mass star population provides an exciting opportunity for the search of potentially habitable worlds. Here, I will follow scientific convention to define "potentially habitable world" as one in which there is the possibility of persistent liquid water on its surface. While worlds with interior oceans (such as the icy moons Europa and Enceladus) or other surface liquids (such as the hydrocarbon lakes on the Saturnian moon Titan) may support the development of novel life forms, life as we know it – Earth-based life – requires liquid water at or near the planet's surface to thrive. Liquid water can exist only on planetary surfaces with an atmosphere and within a specific range of temperatures, 0°C to 100°C at standard atmospheric pressure. The surface temperature of a planet is determined primarily by the amount of radiation it receives from its star, which in turn depends on the star's surface temperature, size, and distance from the planet, as well the fraction of starlight absorbed by the planet surface, and the fraction of thermal radiation emitted out into space. Other heat sources, such as geothermal activity and tidal forces, can also play a role. The primary factors define a star's "habitable zone", the region in which planets could maintain surface liquid water. Not surprisingly, Earth resides in the Sun's habitable zone, but so does the Moon and Mars, illustrating the importance of atmospheres (for the Moon) and the transience of habitability (Mars likely lost its surface water to by exposure to the Solar wind and the atmospheric escape of hydrogen).

The lowest-mass stars have several properties that make them ideal targets in the search for potentially habitable worlds. First, both theoretical calculations and observational studies show that the kinds of planets with surfaces – rocky or icy "terrestrial" worlds – are more likely to form and be found around the lowest-mass stars. Analysis of data from the *Kepler* spacecraft and ground-based

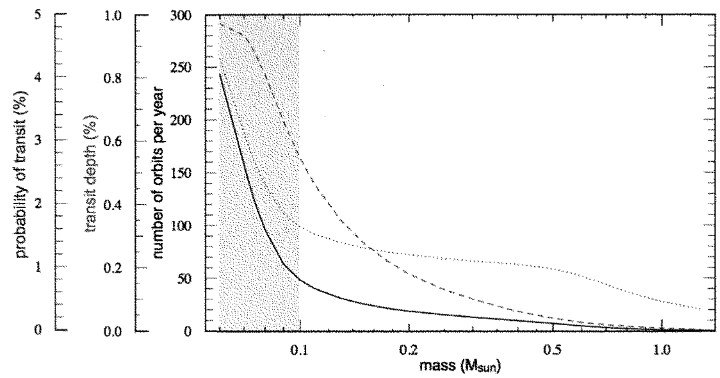


Figure 2: Measures of detectability for transiting Earth-sized planets in the habitable zones of 1 billion-year-old stars of different stellar mass. Curves show the geometric probability of transit (blue dotted line), transit depth (red dashed line) and number of orbits in a year (black solid line). All of these metrics strongly favor searches for planets among the lowest-mass stars (green region). From Triaud et al. 2013, https://arxiv.org/abs/1304.7248.

microlensing surveys find that there are on average 2 Earth-sized planets per low-mass star. Compared to Sun-like stars, low-mass stars have 3.5 times more Earth-sized planets and 50% more terrestrial planetary mass overall. With infrared-sensitive detectors, planets in the habitable zones of low-mass stars are also easier to detect. Because these stars are both cooler and smaller than the Sun, their habitable zones are closer in, so habitable-zone planets have shorter orbital periods. This facilitates their discovery by the radial velocity technique, in which the presence of a planet is inferred by its back-and-forth gravitational pull on the star. The closer the planet, the stronger the pull, and a lower mass star will also exhibit a greater reflex motion. Habitable zone planets are also easier to detect through the transit method, applicable for a small fraction of systems (about 1-4%) in which a planet passes between us and its star, briefly blocking a small fraction of the star's light. The amount of light blocked – the transit signal – is larger for smaller stars, while the probability of transit is greater for closely orbiting planets. For both radial velocity and transit methods, the short orbit periods of close-in habitable zone planets produce more frequent periodic signals, improving the likelihood of their detection.

Low-mass stars may also have pitfalls when it comes to planet habitability, although here there is more uncertainty given our very recent discovery of these systems. Planets orbiting close to their stars are subject to tidal locking, in which the star's gravitational forces cause the planet to rotate so that it always faces one side toward the star (tidal locking is why we see only one side of the Moon from Earth). While initial research suggested that tidal locking would be catastrophic for planet habitability, causing atmospheres to evaporate on the day side and freeze out on the night side, more recent work has shown that heat can be redistributed around a tidally-locked planet even with a relatively thin

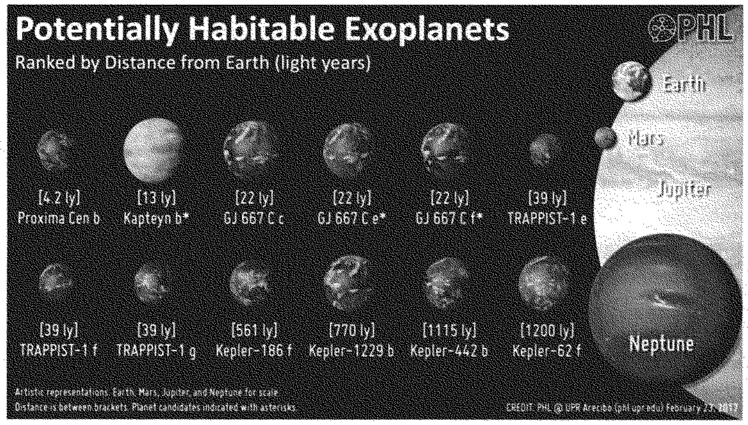


Figure 3: Graphical summary of 12 potentially habitable exoplanets as compiled by the Planet Habitability Laboratory at the University of Puerto Rico at Arecibo. These are the most "conservative" systems, with the highest probability of having surface liquid water. The images of the exoplanets are artistic representations scaled in size relative to the Solar System planets shown at right. The distances and names of the exoplanets are listed, and those marked with an asterisk (*) are still considered candidates. From the PHL website, http://phl.upr.edu/projects/habitable-exoplanets-catalog.

atmosphere. Cloud formation on the dayside can also play a role in stabilizing the environment. Indeed, tidal locking could reduce variations in planetary tilt, resulting in global climates that are *more stable* than Earth, and thus well suited for the development of life. The forces that cause tidal locking can also heat the interior of the planet, potentially driving excessive geothermal activity similar to that seen on Jupiter's volcanic moon Io. Again, while extensive volcanism could be problematic for the development of life, tectonic activity drives many of the chemical cycles (such as the silicate-carbon cycle) that are essential for life on Earth. Low-mass stars are also known to be highly magnetically active, producing high-energy flares and coronal mass ejections with often greater intensity that the Sun. The X-ray and ultraviolet radiation, and high energy particles, emitted by this magnetic activity can damage biological organisms, evaporate the oceans, and strip away the atmospheres of closely-orbiting planets. On the other hand, if the planets themselves had strong enough magnetic fields and ozone in their atmospheres (possibly produced from the oxygen released by evaporating oceans), their surfaces would be shielded from these effects, just as the Earth's magnetic field shields us from the Sun's magnetic storms.

The habitability and evolution of terrestrial planets around the lowest mass stars are among the most uncertain and exciting aspects of this developing area of research, allowing us to explore the origins of life in novel systems. Fortunately, we are entering an era in which both targets (planets) and the tools (technology) will be available to find and characterize these worlds.

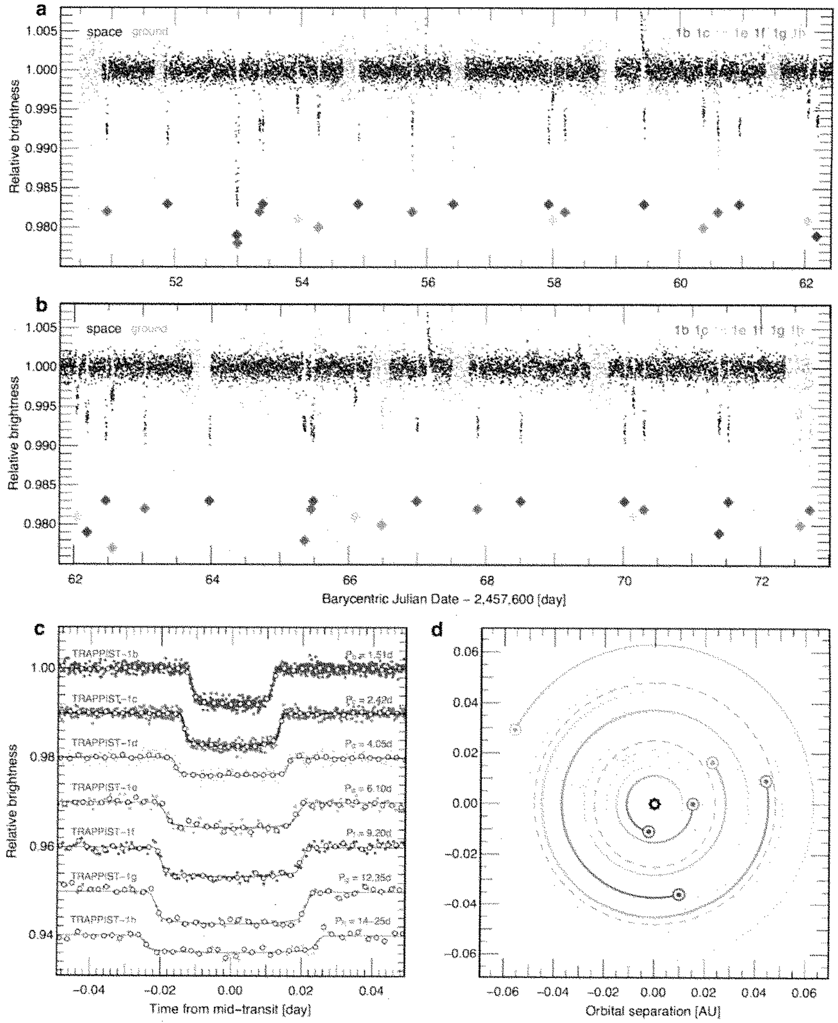


Figure 4: Data leading to the discovery of the TRAPPIST-1 seven-planet system. Panels (a) and (b) show the 22-day light curve obtained in September 2016 with space-based *Spitzer* observations (dark points) and ground-based measurements (grey points). Colored symbols denote the transit times for each of the seven planets. Panel (c) shows the individual transits for each of the planets. The transit depth measures the size of the planet relative to the star, while the transit duration measures the speed of the planet and thus its orbit distance. Panel (d) is a visualization of the planet orbits, with the grey region mapping the TRAPPIST-1's habitable zone. Three planets – e, f and g – orbit within this zone. The axes are measured in Astronomical Units (AU), the distance between the Earth and the Sun. For comparison, Mercury orbits between 0.31 and 0.39 AU from the Sun, about 10 times the distance of TRAPPIST-1f and g. From Gillon et al. 2017, *Nature* **542**, 456.

Discovering potentially habitable terrestrial exoplanets

Given that conditions favor their detection around the lowest-mass stars, it is no surprise that the first discoveries of potentially habitable Earth-sized worlds were made around stars less massive than the Sun. *Kepler*-62f and *Kepler*-186f, each the fifth planet around their respective host stars, were the first potentially habitable planet discoveries, both identified through the transit method with the *Kepler* spacecraft. Similar planets have been found around low-mass stars by the radial velocity method, most notably Proxima Centauri b, a greater-than Earth mass planet orbiting in the habitable zone of the nearest star to the Sun. The University of Puerto Rico Planet Habitability Laboratory maintains an up-to-date list of potentially habitable planets, and categorize 12 planets as "conservatively" likely to have surface liquid water (Figure 3) All of these were discovered in the past 5 years, and all orbit stars less massive than the Sun, most less than one-third the Sun's mass. Eight of the twelve planets are within 40 light-years, considered "very nearby" on a cosmic scale. While there are many selection effects that enter into these statistics, these discoveries nevertheless confirm that potentially habitable worlds are present and detectable around the lowest mass stars.

Earlier this year, three of these planets were discovered by our team as part of a system of seven Earth-sized planets orbiting a very low-mass star 39 light-years from Earth (Figure 4). This star, called TRAPPIST-1, is an ultracool dwarf first discovered with 2MASS data in 2000, and has a mass 8% that of the Sun and a diameter equivalent to the planet Jupiter. All seven planets were detected by the transit method, combining data from ground-based and space-based facilities. Three of the planets – e, f and g – orbit within the star's habitable zone. Because TRAPPIST-1 is dim (emitting less than 0.1% of the Sun's total radiation), these potentially habitable planets orbit close to their star, less than 5% of the distance between the Earth and the Sun. The entire system fits easily within the orbit of Mercury. The seven planets have orbit periods between 1.5 and 18.8 days and are organized in "resonance chains" that cause them to gravitationally pull on each other in their orbits, a phenomenon we can discern by variations in their transit times of up to 40 minutes. Overall, this small, compact system looks more like the Galilean moon system around Jupiter than the Sun's planetary system, a potential clue to its origin.

Our discovery was possible thanks to an international collaboration of scientists from two dozen institutions in ten countries on four continents, including US researchers based in the states of California, Maryland, Massachusetts, Texas, and Washington. In 2015, our team reported the detection of three transiting planets orbiting TRAPPIST-1 based on observations obtained with the TRAnsiting Planets and PlanetesImals Small Telescope South (TRAPPIST-South), a 60-cm robotic telescope located in Chile. A second telescope, TRAPPIST-North, is in operation at Oukaïmden Observatory in Morocco (Figure 5). Both facilities are operated by the University of Liege, Belgium, and led Dr. Michael Gillon with support by European research funds. We found two close-in

Figure 5: The TRAPPIST facilities at the ESO La Silla Observatory in Chile (left) and the Oukaïmden Observatory in Morocco (right). Both are 60 cm robotic telescopes optimized for the detection and characterization of exoplanets and small bodies in our solar system. (Photo credit: Emmanuel Jehin)

planets too hot to sustain life; and a third candidate habitable zone planet with only two transit detections and a highly uncertain orbit period. Uncertainties in planet detections are common for ground-based transit programs, as data can only be acquired at night, in good weather, and when the star is well above the horizon, resulting in significant sampling bias. As we continued to monitor this star using facilities in Chile, South Africa, the United Kingdom, Spain, Morocco and the US, we began to see evidence that there were more planets in the system. We turned to the *Spitzer* Space Telescope, a NASA-funded infrared space facility launched in 2003 onto an Earth-trailing orbit around the Sun. As a stable, space-based platform, *Spitzer* provides exceptional brightness measurements with no day/night or weather interruptions. Monitoring TRAPPIST-1 with *Spitzer* for 21 days along with concurrent ground-based observations revealed 92 transits that could be assigned to seven distinct planets. These results were subsequently verified in a 74-day monitoring campaign conducted by the NASA-funded *Kepler* space telescope, with data released to scientists and the public last month.

Beyond revealing the presence of a planet, the transit method yields measurements of its size relative to its star. Our observations and analysis of the TRAPPIST-1 star show that the planets are between 0.7 to 1.1 times the size of the Earth. In addition, the transit timing variations observed for these planets have yielded the first estimates of the masses of the planets (0.09 to 1.6 times the mass of Earth) and their average densities (0.2 to 1.4 times the density of Earth). These measurements currently have large uncertainties but will improve with time. Importantly, the indicate that the planet's interiors are dominated by rock and volatiles, the latter including liquid and solid water, carbon dioxide and ammonia. These worlds may be the first ocean worlds to be discovered in the habitable zone of a star, which would have profound implications on the search for life beyond the Solar System.

The TRAPPIST-1 system establishes several exoplanet firsts, including the lowest-mass star known to host planets and the largest number of Earth-sized worlds found around any star (including the Sun). It is arguably the most promising system to date in the search for life beyond our Solar System, with at

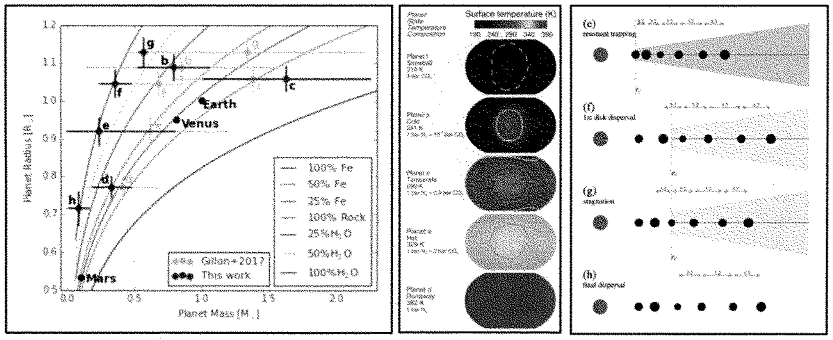


Figure 6: Characterization of the TRAPPIST-1 system. (Left) Planet radii and masses measured from transits and transit timing variations compared to models of interior composition. This study predicts that the habitable zone planets – e, f and g – may have interiors of up to 50-100% water. (Middle) Surface temperature maps of planets d, e and f based on climate modeling. (Right) One possible scenario for the formation of the TRAPPIST-1 system based on migration and circumstellar disk interaction. (Figures from Wang et al. 2017, submitted to Astrophysical Journal, https://arxiv.org/abs/1704.04290; Wolf 2017, Astrophysical Journal Letters 839, L1; and Ormel et al. 2017, submitted to Astronomy & Astrophysics, https://arxiv.org/abs/1703.06924).

least three chances at a habitable world. The system has energized the scientific community, with over a twenty follow-up studies published since the full system was announced in February 2017. These studies are exploring the origin, orbits, composition, and climates of the planets, as well as the space environment around by the star (Figure 6).

Yet TRAPPIST-1 is only one of many systems with habitable zone Earth-sized worlds around low-mass stars that we expect to find over the next several years. Just last week, the NSF-funded MEarth project, which has deployed a network of 40-cm telescopes in Chile and Arizona for its own search for planets around low-mass stars, reported the discovery of a super-Earth (6.6 times the mass of Earth) in the habitable zone of a star that has 15% the mass of the Sun and is also 39 light-years away. As the TRAPPIST and MEarth programs continue, our team will also be expanding our ground-based transit search through the Search for habitable Planets EClipsing ULtra-cOOl Stars (SPECULOOS) project, with four 1-meter robotic telescopes optimized for the lowest-mass stars currently under construction in Chile. These ground-based programs will soon be joined by the NASA-funded Transiting Exoplanet Survey Satellite (TESS), scheduled for launch in March 2018, which is expected to discover hundreds of planets around the nearest and brightest low mass stars. Other program, funded by NASA, NSF, and international funding agencies, are also gearing up to identify planets around low-mass stars through the radial velocity and microlensing techniques, using new instrumentation and multi-telescope systems sensitive to dim red stars.

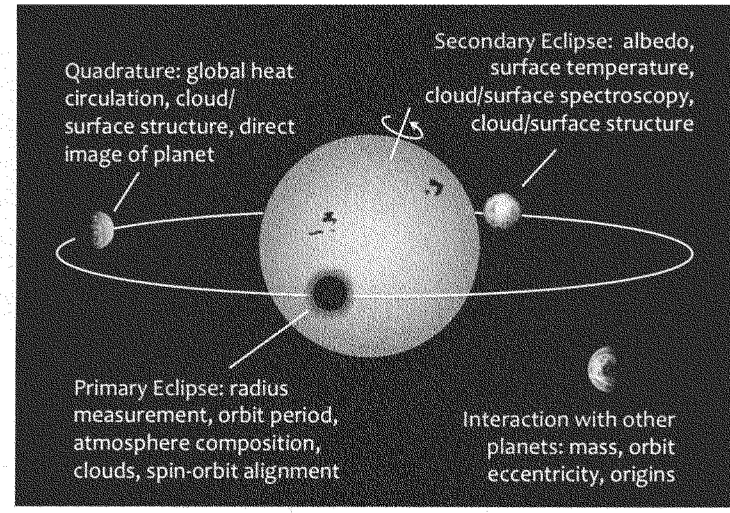


Figure 7: Methods for characterizing planets transiting a low-mass star.

The number of potentially habitable worlds around the lowest mass stars is expected to increase dramatically over the next several years, and with that comes an opportunity to directly search for evidence of life on other worlds.

From discovery to planet characterization to the search for life

Determining whether a potentially habitable planet is in fact habitable requires observations of its atmosphere and surface. Astronomers have developed a number of techniques to do these challenging measurements (Figure 7). During transit, spectroscopic observations can be used to measure the gas composition of the atmosphere and infer the presence of high-altitude hazes and clouds. These measurements may provide evidence for atmospheric water vapor, which would link directly to the presence of surface liquid water; they can also probe geothermal processes (volcanism) and life (biogenic gases). Transit observations can also assess the stability of an atmosphere through the search of trailing absorption features, signatures of atmospheric gases escaping from the planet. Additional dips in starlight following a planet's transit could signal the presence of a large moon. When the planet passes behind the star, a phase known as secondary eclipse, starlight reflected by the planet's clouds or surface can be used to infer their composition and structure. Infrared observations at this phase can measure the temperature of the planet, and with spectroscopy the dayside surface or atmospheric composition. As the planet orbits between these two phases, variations in the combined light of star and planet can constrain both heat circulation and cloud/surface structure around the planet. For planets on wider orbits, quadrature is the optimal phase to obtain a direct image or spectrum

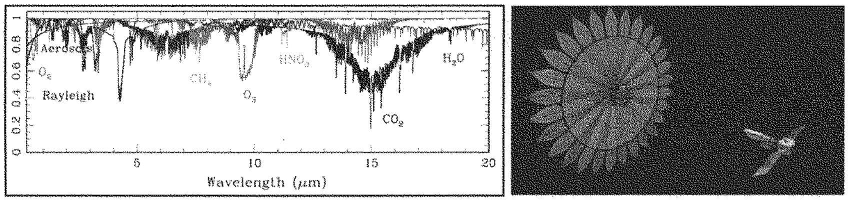


Figure 8: (Left) Model transit spectrum of an Earth-like world, showing the locations of water vapor and potential biogenic gases. JWST will be sensitive across the entire wavelength range shown. (Right): Visualization of the Starshade concept by NASA for direct exoplanet imaging. An external occulting array is placed up to 50,000 kilometers in front of a space telescope like WFIRST to suppress the planet's host starlight. (From Kaltenegger & Traub 2009, *Astrophysical Journal* **698**, 519; and NASA/JPL)

of the planet. Some of these measurements can be achieved for non-transiting planets as well, although the separation of star and planet light becomes more challenging.

Each of these measurements has been achieved for the largest transiting exoplanets (Jupiter- and Neptune-like gas giants) and attempted for Earth-sized planets around low-mass stars (including TRAPPIST-1), using large ground-based telescopes and the *Hubble Space Telescope* (HST). Unfortunately, these facilities do not have the sensitivity to detect the spectroscopic signatures of an Earth-like atmosphere (e.g., CO_2 or O_2-rich) or reflectance signal from a terrestrial world. Extending these techniques to potentially habitable worlds will require the next generation of ground-based and space-based facilities. Very large telescopes in the 25-35 meter diameter range, including the Thirty Meter Telescope (TMT), the Giant Magellan Telescope (GMT) and the European Extremely Large Telescope (E-ELT), coupled with advanced instrumentation, should have the resolution and sensitivity to detect Earth-sized planets around low-mass stars with the radial velocity technique, as well as measure the atmospheres of transiting and non-transiting super-Earth planets around these stars. These facilities are expected to come online in the next decade. The *James Webb Space Telescope* (JWST), HST's successor with a planned launch in late 2018, will extend atmospheric characterization to Earth-sized worlds in the habitable zones of the lowest-mass stars, particularly at mid-infrared wavelengths where several important biomarkers (e.g., oxygen, ozone, methane and nitrogen-oxide compounds; Figure 8) have strong absorption features. JWST will also have the sensitivity to measure the thermal emission from these worlds during secondary eclipse, allowing us to map out heat circulation to assess the overall environments of these planets. Again, such measurements favor systems around the lowest-mass stars, and could reveal evidence of liquid water or life on any of these worlds.

Full characterization of potentially habitable worlds will ultimately require direct detection of their surfaces and atmospheres, a task made challenging by the overwhelming glare of the star the planet orbits. NASA's Exoplanet Exploration program will be a critical asset in this endeavor, as only space-based facilities will have the stability, sensitivity and capability of imaging a potentially habitable world around another star. Following JWST, the Wide Field Infrared Space Telescope (WFIRST), the top priority among large space missions from the 2010 National Academy of Sciences Astronomy Decadal Review, will greatly increase the number of known exoplanets, particularly through the microlensing technique. For direct detection, NASA scientists and engineers are now exploring the feasibility of matching WFIRST to an external occulter to suppress starlight – the Starshade concept – a facility that could directly image an Earth-like world around a Sun-like star by 2030, if implemented. This facility won't be able to resolve planets in the close-in habitable zones of the lowest-mass stars, but the technology does pave the path for future direct imaging missions of these systems, possibly through concept missions Habitable Exoplanet Imaging Mission and the Large UV/Optical/Infrared Surveyor. Meanwhile, the Origins Space Telescope would provide detailed chemistry of the atmospheres of these planets in the far infrared. If selected, these facilities would conduct observations in the 2030s and 2040s.

While the potential for an image of an Earth-like world in the next 15-25 years is exciting in its own right, it is worth noting other ambitious programs aimed at exploring these worlds in different ways. These include the Breakthrough Initiative Starshot project that aims to propel ultralight satellites at high speeds to the nearest stars through laser propulsion; and the search for signals from advanced life forms across the electromagnetic spectrum through the Search for Extraterrestrial Intelligence (SETI) project. These public-private partnerships will have plenty of potentially habitable worlds to target among the many low-mass stars in the immediate vicinity of the Sun.

Concluding Remarks

Our recent advances in the search for habitable worlds and life beyond our Solar system has captured the imagination of people around the world, including US citizens of all backgrounds. After the announcement of TRAPPIST-1 was made in February 2017, I and my colleagues have had hundreds of conversations with children and parents, students and teachers, scientists and artists, Uber drivers and airline pilots, janitors and Senators, friends, family and complete strangers, people from all walks of life who are curious about these worlds and what they mean for life on and beyond Earth. I have personally received emails, texts, tweets and good old-fashioned letters suggesting names for the planets, presenting personal artwork (Figure 9), and sharing stories both fiction and non-fiction inspired by this discovery. These messages reflect a diversity of engagement with science, technology, engineering and math that extend beyond the classroom. Research leading to the discovery of new worlds is also broadly accessible to young scientists and the public alike, thanks to the open data policy of federally-funded programs. In my own lab, I have had high school students and teachers from local underserved school districts, undergraduates from minority-serving institutions, and graduate students from around the world

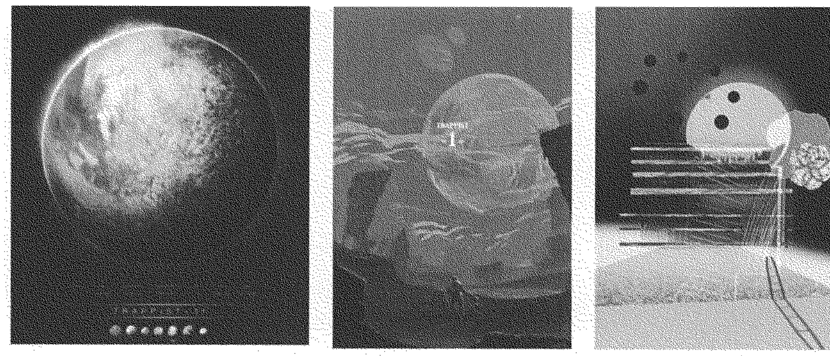


Figure 9: Examples of creative work by artists inspired by the TRAPPIST-1 discovery. From left to right: Guillem Pongiluppi (https://www.artstation.com/artwork/nLnEO), Kontorn Boonyanate (https://www.artstation.com/artwork/LBYov), and Amanda J. Smith (http://www.trappist.one/#posters).

working on these data to better understand the stars and planets we have found. And many people are excited to learn that they can be directly involved in the search for habitable worlds through citizen science programs such as Planet Hunters, Exoplanet Explorers, Backyard Worlds, SETI@home, and Project Panoptes, to name a few. There is undeniably a broad interest among our fellow citizens to be part of the search for life beyond Earth.

Continued federal funding of a diverse portfolio of research programs is critically essential to this work. None of this is possible without public support. Federal funding is also critical for maintaining US leadership not just in astrobiology and space science, but in science and technology in general. The search for life beyond Earth requires advanced observational facilities and instrumentation on Earth and in space, computational facilities and data science programs to process the petabytes of data from current and future missions, theoretical work to understand the origins and evolution of other worlds, and laboratory experiments to explore the diverse biochemistry of life in environments that may exist on these worlds, among other areas. As in all basic research programs, public investment and public-private partnerships in this area will have broad impacts on society through technology development, new materials, biomedical applications and computational advancements. Perhaps most important are the educational and public outreach initiatives that not only share these exciting discoveries with the nation, but train the next generation of scientists to tackle a broad range of challenges and opportunities we have now and in the future.

This generation is the first in human history to know that there are other worlds beyond our Solar System. Will the next generation know that life exists on those worlds? We have both the opportunity and the responsibility to continue our nation's legacy of exploration and discovery so that our children and grandchildren will know more about life in the Universe than we can even hope to imagine.

Dr. Adam J. Burgasser

Short Narrative Biography

Dr. Adam Burgasser is a Professor of Physics at UC San Diego and an observational astrophysicist investigating the lowest mass stars, coldest brown dwarfs, and exoplanets. He uses a variety of ground-based and space-based telescopes to discover and research the physical properties of these objects across the electromagnetic spectrum. He has authored or co-authored over 175 peer-reviewed publications over his career, including contributions to the discovery of seven Earth-sized planets around the nearby low-mass star TRAPPIST-1. Dr. Burgasser also conducts education research in physics, examining cooperative and flipped-model learning strategies in large-format physics courses; and interdisciplinary research along the science-art continuum, examining data-driven artforms, trans-sensory perception, and participatory public science-art installations. In 2016, he was awarded UCSD's Distinguished Teaching Award.

Dr. Burgasser is committed to improving equity and inclusion in the sciences, by identifying and addressing barriers for underrepresented groups. He has chaired the American Astronomical Society (AAS) Committee on the Status of Minorities in Astronomy, directs the UC-HBCU UCSD-Morehouse-Spelman Physics Bridge Program, and was part of the organizing committee that hosted the first Inclusive Astronomy conference at Vanderbilt University in 2015. In 2014, he was awarded the Equal Opportunity/Affirmative Action and Diversity Award at UC San Diego for his diversity and outreach work.

Dr. Burgasser earned his B.S. in Physics at UC San Diego in 1996, where he was also a national champion springboard diver and recipient of the NCAA Top VII award. He earned his Ph.D. in Physics (with a specialization in Planetary Science) from the California Institute of Technology in 2001. Dr. Burgasser conducted postgraduate work as a Hubble Postdoctoral Fellow at UC Los Angeles and a Spitzer Postdoctoral Fellow at the American Museum of Natural History in New York City. He has held faculty positions in the Departments of Physics at MIT and UC San Diego. In 2017, he was awarded a Fulbright scholarship to conduct research at the University of Exeter.

Dr. Burgasser's astrophysical, educational and creative research work has been supported by the National Science Foundation, NASA, the American Astronomical Society, the American Physical Society, the MIT Alumni Class Funds, the UC Office of the President, the UC Institute for Research in the Arts, the UCSD Center for the Humanities, the UCSD Frontiers in Science Program, the UCSD Office of Equity, Diversity and Inclusion, the UCSD Division of Physical Sciences, Fulbright Program, and the Chris and Warren Hellman Fellowship.

Chairman SMITH. Thank you, Dr. Burgasser.
And Dr. Kasting.

TESTIMONY OF DR. JAMES KASTING, CHAIR, PLANNING COMMITTEE, WORKSHOP ON THE SEARCH FOR LIFE ACROSS SPACE AND TIME, NATIONAL ACADEMIES OF SCIENCE, ENGINEERING, AND MEDICINE, EVAN PUGH PROFESSOR OF GEOSCIENCES, PENNSYLVANIA STATE UNIVERSITY

Dr. KASTING. Chairman Smith, Ranking Member Johnson, and Members of the Committee, thank you for allowing me to testify at this hearing. I was selected for this spot because I chaired the Planning Committee for the recent National Academies' workshop on searching for life across space and time.

In my written testimony, I've attempted to summarize key points made by various participants at that workshop. Here I will focus on two important new discoveries, one within our solar system and another outside of it. I should emphasize that I'm speaking on my own behalf as an active researcher and not on behalf of the National Academies.

The new solar system measurement was made by NASA's Cassini spacecraft, which has been orbiting Saturn for the last 12 years. Chairman Smith already mentioned this. One of the objects the Cassini has studied is Saturn's moon Enceladus, which is shown on the slide. Enceladus is of great interest to astrobiologists because, like Jupiter's moon Europa, it's thought to have a subsurface ocean. Part of the evidence for this ocean is a plume of material emanating from Enceladus' south pole. During its lifetime, Cassini has performed multiple passes through this plume, sampling the gases that make it up. Previous measurements had already determined that the plume consists mainly of water vapor with smaller amounts of carbon dioxide and methane.

As many of you already know, NASA is about to bring the Cassini Mission to an end by plunging the spacecraft into Saturn sometime late this summer. With the end in sight, flight controllers have been taking more risks with the mission over the past two years. In 2015, Cassini made its deepest penetration yet through the plume, passing within 49 kilometers of the moon's surface. The mass spectrometer was also operated in a different mode that allowed it to measure molecular hydrogen. This in turn allowed researchers to estimate the amount of chemical energy available within Enceladus' ocean from the reaction between carbon dioxide and hydrogen to make methane. This reaction is used by methanogens here on Earth to power their metabolisms.

The new results indicate there should be enough chemical energy available within the ocean to support methanogens. This of course does not mean that life is present on Enceladus, however, it suggests that the search for life there could be rewarding. Next slide, please.

[Slide.]

My second update concerns rocky planets that have been discovered orbiting within the habitable zones of nearby red dwarf stars, also known as M stars. Adam Burgasser just told you about the planets orbiting TRAPPIST–1 and about the other new exoplanet announced last week that orbits this M star LHS–1140.

All of these planets were discovered from the ground by looking for transits in which the planet passes in front of its parent star. During transit, some of the starlight passes through the planet's atmosphere, allowing its composition to be studied spectroscopically. This has been done previously for giant planets using the existing Hubble and Spitzer space telescopes but it will be done much more accurately by NASA's upcoming James Webb Space Telescope, JWST, which launches late next year. The hope is to look for the presence of possible biosignature gases, especially molecular oxygen, O2, which is produced by photosynthetic plants and algae here on Earth.

A third new exoplanet discovery announced late last summer, which you also have heard about already, is a rocky planet orbiting within the habitable zone of the nearest M star, in fact, the nearest star, Proxima Centauri. This planet was discovered from the ground by a team of European astronomers using the radial velocity method. This technique uses the Doppler effect to look for the back-and-forth motion of the star caused by planets orbiting around it. Because the Proxima Centauri planet probably does not transit, it is harder to study with JWST. The planet is close enough, however, that it can potentially be characterized from the ground using planned 30- to 40-meter telescopes. By again using the Doppler effect, researchers can separate the absorption lines in the planet's atmosphere from lines formed within the Earth's atmosphere, allowing them to look for biomarker gases such as oxygen and ozone.

Ultimately, astrobiologists would like to look for Earth-like planets orbiting more stars more like the sun. This will require large space-based direct imaging telescopes that have not yet been approved. The good news is that NASA is again studying them. Hopefully within the next 15 to 20 years, we'll be able to search for habitable planets and life around all the stars within the solar neighborhood.

Thank you again for allowing me to testify at this hearing.

[The prepared statement of Dr. Kasting follows:]

Statement of Dr. James F. Kasting
Evan Pugh Professor of Geosciences
Penn State University

before the

Committee on Science, Space, and Technology
U.S. House of Representatives
April 26, 2017

Chairman Smith, Ranking Member Johnson, and Members of the House Committee on Science, Space, and Technology, thank you for allowing me to testify at this important committee hearing. I was selected for this spot because I chaired the planning committee for a recent National Academies' workshop entitled "Searching for Life Across Space and Time" held on Dec. 5-6, 2016, in Irvine, CA. Henceforth, I will refer to this as the 'Biosignatures Workshop'. As you will recognize, an Academies' workshop is a venue for discussion and debate—an essential effort in allowing the scientific process to unfold. Published proceedings chronicle the presentations and discussions that take place at these types of Academies' activities, and the proceedings from the December event will be published later this Spring. My testimony today will attempt to summarize my personal perspective on key points made by various participants at that workshop. However, I will update this story with four important discoveries, three of which were announced after the workshop was held. And I will attempt to show how the present search for life relates to the ongoing search for intelligent life, which was *not* discussed at the workshop. I should emphasize that I am speaking in my personal capacity as an active researcher and am not speaking on behalf of the National Academies of Sciences, Engineering, and Medicine.

Relation of the search for life to SETI

Interest in the search for life off the Earth has been growing continuously over the last four decades. Many of us are ultimately motivated by the Search for Extraterrestrial Intelligence (SETI), which has been going on for that amount of time, or longer. We would like to know whether there is someone else to talk to out there in the galaxy, or in the larger Universe. The late Carl Sagan helped pioneer this search and inspired millions of people worldwide, including me, to share his aspirations.

In a logical world, however, SETI would have been preceded by a search for less complex forms of life. If life does originate in places other than Earth, then simple life forms are probably more abundant than complex or intelligent life forms, according to the Drake equation that Carl Sagan helped formulate (along with Frank Drake). We started looking for intelligent life first because the technology for building radio telescopes matured well before that needed to look for life itself. Looking for simple life is *difficult*. Within the solar system, we can do this most effectively by sending spacecraft to other planets and observing them either from orbit or from landers/rovers, like the Curiosity rover that is exploring Mars right now. Outside of the solar system, astronomers have identified numerous exoplanets from the ground using the radial velocity, or Doppler, method. More recently, our knowledge of exoplanets has exploded as a result of NASA's successful Kepler Space Telescope mission. Kepler found planets by detecting their transits in front of their parent stars. Thanks to Kepler, we now know the addresses of thousands of exoplanets, and we also know that most stars are accompanied by two or more planets. But we know virtually nothing about whether any of these planets are habitable or inhabited. Figuring this out is our biggest goal for the future.

Subdividing the search for life

At the recent Biosignatures Workshop, we divided the search for extraterrestrial life into four quadrants, as shown in Fig. 1. The two vertical columns represent in-situ life detection (which we can do in the solar system) and remote life detection (which is all that we can hope to do for exoplanets, given present technology). The two horizontal rows represent life 'as we know it' and life 'as we don't know it'. We don't really know how different alien life would be from us, and this affects where we think to look for it, as well as the techniques we might use to identify it.

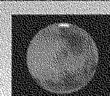
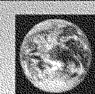
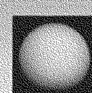
	In situ detection (Solar System)	Remote detection (Exoplanets)
Life as we know it		
Life as we don't know it		?

Fig. 1 Schematic diagram showing the four different conceptual areas in the search for life off the Earth. The planetary bodies that are representative of three of these areas are (clockwise from the upper left) Mars, Earth, and Saturn's moon, Titan. The fourth area is undefined for the moment, and likely to remain so.

In situ detection of life as we know it

Mars

Life as we know it here on Earth shares many common characteristics. At its most basic level: 1) Life is carbon-based, 2) it requires the presence of liquid water at least some of the time, and 3) it utilizes the molecules DNA and RNA to store and transfer genetic information. Mars is one planet within the solar system where we might search for this type of life. Indeed, various researchers have proposed that life could have been transferred from Mars to Earth, or vice versa, by meteorites. So, it might not actually be surprising to find DNA-based life on Mars. One workshop participant, Gary Ruvkin from Harvard Medical School, suggested sending a modern, mobile DNA sequencer to Mars. Such machines can detect and analyze extraordinarily small samples of DNA, and would likely be able to find Earth-like life if it was there. But if martian organisms don't rely on DNA, then such a search would be fruitless even if Mars was teeming with life.

Big strides in Mars' exploration have been taken over the last few years by the Mars Exploration Rovers, which began their mission in 2003, and by the Curiosity rover, which has operated since 2014. John Grotzinger from Caltech, who has been involved in both missions, gave an overview of Curiosity results, highlighting the evidence for long-lived lakes. Jennifer Eigenbrode from NASA's Goddard Space Flight Center talked about detection of organic compounds. Organic compounds have indeed been found, but that is to be expected because of continual meteorite bombardment. Bottom line: Curiosity has found additional evidence of habitability—i.e., an environment with conditions appropriate to the support of life at some time in the past—but nothing that would definitely indicate present or past life. Curiosity has also reported seeing methane, in agreement with ground-based observations, but that finding remains controversial. (Some researchers have argued that Curiosity brought the methane with it from Florida.) The ESA-Russian ExoMars Trace Gas Orbiter mission, which is at Mars now and will achieve its science orbit early next year, will hopefully answer this question.

Mars exploration is proceeding at a good rate, with missions launched at nearly every 2-year opportunity. The big debate is whether to concentrate on additional orbiters and rovers, sample return, or human exploration. I will not attempt to weigh in on this question. This will be one of the issues discussed by the 2022 planetary science decadal survey, organized by the National Academies of Sciences, Engineering, and Medicine.

Ocean worlds

Jupiter's moon, Europa, and Saturn's moon, Enceladus, both harbor subsurface oceans and could also conceivably be home to life as we know it. But they differ from Mars in the sense that transfer of life between the outer solar system and Earth is considered unlikely. So, if we were to find life on one of these moons, it would likely indicate that life originated more than once—a point made by JPL's Kevin Hand at the workshop. This in itself would be a discovery of enormous importance, as we still do not know whether the origin of life is a chance event, or whether it happens whenever the circumstances are right. Possible life forms on these moons could still be carbon-based and require liquid water, but whether they would utilize DNA and RNA is an open question that biologists would love to answer.

Update #1: The most exciting news in this field is the recent announcement (made well after the workshop) that molecular hydrogen, H_2, has been identified in the plume emanating from Enceladus' south polar region (J.H. Waite et al., *Science*, 2017). The Cassini spacecraft has flown through the plume multiple times and had previously identified CH_4 (methane) and CO_2 (carbon dioxide), in addition to the major constituent H_2O. Finding H_2, and measuring its concentration relative to H_2O, allowed researchers to estimate the thermodynamic *free energy* available from the reaction: $CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$. This is one of the reactions used by methanogenic bacteria here on Earth to power their metabolism. The Cassini researchers calculated that the available free energy in Enceladus' subsurface ocean was an enormous 80±20 kJ/mole. To put this in perspective, methanogens on Earth can typically draw H_2 down until they are only getting about 10-15 kJ/mole. Synthesizing ATP (adenosine tri-phosphate) from ADP (adenosine di-phosphate) requires 35.6 kJ/mole. ATP is the standard unit of energy 'currency' for terrestrial organisms. If the new analysis is correct, there is plenty of free energy available to sustain life in Enceladus' ocean. But we are left to ponder why, if methanogens are there, have they not drawn H_2 down to lower concentrations, as they do here on Earth. Could it perhaps be because they are limited by other factors, e.g., nutrient supply? Given the uncertainties, it would clearly be wrong to conclude at this time that Enceladus is inhabited. But there is lots of incentive to study this object further.

Progress in learning about ocean worlds has been greatly accelerated by the approval of funds for NASA's Europa Clipper mission. Clipper will make multiple passes by Europa and may be able to sample plumes that have been reported based on observations from the Hubble Space Telescope. Clipper should also be able to determine the thickness of Europa's icy crust and take spectra of the brownish material that is thought to ooze up through the cracks. A Europa lander mission, which has been extensively studied but not yet been approved, could take this search even further. It is considered to be technically difficult, though, because of the intense charged particle radiation environment on and around Europa.

In situ detection of life as we don't know it

Titan

Some biologists (and chemists) who like to think 'out of the box' have suggested that life may be a more general phenomenon than what we encounter here on Earth. A formal report issued by the National Academies in 2007, entitled *The Limits of Organic Life in Planetary Systems*, examined this hypothesis in some detail. Informally, this document is sometimes referred to as the 'Weird Life' report. NASA and NSF co-organized a recent 'Ideas Lab' to follow up on this report. Life on Saturn's moon Titan, if it exists, would fall into this category. Titan, which has been explored over the past 15 years by the NASA-ESA Cassini mission and the accompanying Huygens probe, sports lakes of liquid methane. The mean surface temperature is a frigid 93 K, compared to 288 K here on Earth. Whether or not life could originate or survive on Titan is unknown. Earth-like life obviously could not, but perhaps there is some kind of life that could. Finding life on Titan would be even more profound than finding life on Enceladus or Europa because it would suggest that life is an extremely general phenomenon. Some astrobiologists, including me, are skeptical about this idea; however, it is a testable hypothesis that deserves consideration. Indeed, Ellen Stofan proposed a Discovery-class space mission to drop a boat into Titan's methane seas and sample them. Stofan's mission was turned down, not because it lacked scientific merit, but because no one thought it could fit under the Discovery cost cap. It will likely be done someday, not necessarily to find life, but just to see what is there.

Remote detection of life as we know it

Exoplanets

The search for life as we know it extends to exoplanets, as well. None of the other planets in the solar system are truly Earth-like; they differ greatly in their masses, and of course they are all at different distances from the Sun. But rocky exoplanets within the liquid water 'habitable zones' around their parent stars could conceivably be Earth-like. We will not be able to explore them directly, however, at least for the foreseeable future, and so we will have to rely on remote life detection techniques. Life that is present at the surface of a planet can modify the planet's atmosphere in a way that is remotely detectable, using spectroscopy. This falls within my own area of expertise, and so I can report on developments in this area with some degree of confidence.

It was recognized many years ago (Joshua Lederberg, *Nature*, 1964) that Earth's atmosphere is well out of thermodynamic equilibrium and that this is largely due to the presence of life. But thermodynamic disequilibrium, by itself, is not necessarily a sign of life. I have just argued above that the high availability of free energy in Enceladus' ocean—a sign of thermodynamic disequilibrium—could actually indicate that methanogenic life is *not* present. Earth's atmosphere is in extreme disequilibrium for a specific reason: Photosynthetic organisms living on its surface produce O_2 as a byproduct of using H_2O to reduce CO_2 to organic matter. Most of the very large amount of O_2 in Earth's atmosphere, 21 percent by volume, was produced in this way. At the same time, there are anaerobic (O_2-free) regions on Earth where methanogens can produce CH_4. Other anaerobic organisms (denitrifying bacteria) produce nitrous oxide, N_2O, which is also a reduced gas that can react with O_2. Thus, *the simultaneous presence of significant quantities of O_2 and a reduced gas such as CH_4 or N_2O* remains the best remote biosignature that we know of. This realization has not changed substantially for the last 50 years.

Progress has been made, however, in identifying other, somewhat more ambiguous, biosignatures. Some researchers prefer to call these 'biohints'. Our own research group makes computer models of Earth's atmosphere during the Archean Eon, which lasted from 3.8 to 2.5 billion years ago. O_2 was not yet abundant during this period, but life was most certainly present during most or all of this time. Our models suggest that CH_4 should have been abundant during this time period, perhaps accompanied by organic haze. So, early Earth could have looked a little bit like Titan. We would be able to distinguish an 'Earth' from a 'Titan', however, because the 'Earth' would be much warmer and its atmosphere would contain H_2O and CO_2, as well. Both of these gases are completely frozen out of Titan's atmosphere.

Significant attention has also been paid to the question of whether O_2 by itself could be considered a biosignature. This question is motivated by the fact that O_2 would be much easier to spot in Earth's atmosphere than would CH_4 or N_2O, because of its much higher concentration. So, if other Earth-like planets do exist, but not around the very nearest stars, we may well encounter this situation. Consequently, theoreticians like myself have spent considerable time and energy studying the possibility of *false positives* for life, i.e., planets that might accumulate high levels of atmospheric O_2 without life being present. I will mention just one of these false positives here, because it is the easiest to understand: Suppose that you had a planet like early Venus that was initially endowed with lots of water, but that lost that water because it was too close to its star, and so it experienced a *runaway greenhouse*. The H_2O would be photodissociated by stellar ultraviolet radiation, the hydrogen would escape to space, and O_2 would be left behind. Fortunately, this particular false positive would be easy to identify, because the water would be gone. (Unless, of course, we caught the planet right in the act of losing its water. But we would be suspicious of such a planet, anyway, because it would lie within the inner edge of its star's habitable zone.)

I will not bore you with a lengthy discussion of all of the possible false positives, or the ways we might have of ruling them in or out. As I said, there is a growing literature on this topic, which is available on request. I should say that much of this research has been funded by NASA's R&A programs, particularly Exobiology, Habitable Worlds, Emerging Worlds, and the NASA Astrobiology Institute. NASA has been forward-looking in funding these programs, which are helping to lay the groundwork for the interpretation of future exoplanet spectra. As a result, there is now a community of researchers, many of them young (unlike myself), who are poised to take advantage of such data when they become available.

Planets around M stars

Planets orbiting M stars (dim red-dwarf stars) deserve special mention because they are the ones that are most likely to be observed over the next 10-15 years. An Earth-like planet is, by definition, roughly Earth-sized, whereas M stars are significantly smaller than the Sun. Thus, M-star planets create a deeper dip in the star's light when they *transit* (go in front of) the star. The habitable zone of an M star is also much closer to the star (because the star is so dim), and hence the probability of a transit is higher. When the planet transits the star, a small amount of the star's light passes through the planet's atmosphere, and this can be examined spectroscopically. Consequently, M-star planets can be studied with existing and planned space telescopes. Existing telescopes (Hubble and Spitzer) have only been able to characterize gas or ice giant planets (hot Jupiters and warm Neptunes). But the James Webb Space Telescope (JWST), which launches next year, *may* be able to obtain spectra of a few rocky, habitable-zone planets. This, of course, is an extremely exciting prospect.

Update #2: Another major discovery that was announced after the December Biosignatures workshop was the existence of 7 planets orbiting the M star TRAPPIST-1. I will not say much about this discovery, as Adam Burgasser (who was on the TRAPPIST team) will presumably cover this topic in his testimony. At least three of these planets are within their star's habitable zone, and so characterizing these planets spectroscopically has already become a major science goal for JWST. This discovery, like the two that follow, was made using ground-based telescopes.

Update #3: A new transiting, habitable-zone planet was announced just last week orbiting the M star LHS1140 (J.A. Dittmann et al., *Nature*, 2017). This planet was found by the MEarth survey, headed by David Charbonneau of Harvard University. The star is roughly twice as massive as TRAPPIST-1, weighing in at ~0.15 times the mass of our Sun. This will be another likely target for JWST.

Update #4: There is a rocky planet orbiting within the habitable zone of the nearest star, Proxima Centauri. This should actually be update #1, as it was announced at the end of last summer, well before the workshop. It caused quite a buzz at the workshop, and we had a talk by one of the co-discoverers, Matteo Broge. Broge works at the European Southern Observatory (ESO) in Chile and is a member of the HARPS team. HARPS is a high-resolution spectrograph used for making radial-velocity measurements on stars. This discovery is quite unlike the TRAPPIST-1 and LHS1140 discoveries, because Proxima Centauri b, as the planet is called, does not transit. It therefore cannot be observed by JWST in the same way that the TRAPPIST-1 planets can. Instead, if we wish to characterize this planet spectroscopically, we will have to do *direct imaging*: separating the light reflected by the planet from that emitted by the star. This can be done either by placing a *coronagraph* within the telescope or, if the telescope is in space, by placing a *starshade* at some distance in front of the telescope to block the light from the star. Because Proxima Centauri is an M star, it may be possible to directly image its planet from the ground. Broge and his colleagues are designing instruments for one of the 8-m ESO telescopes in the hopes of doing this. Whether they will succeed is uncertain, according to him. Within the next 10-12 years, however, the astronomers in the US, Europe, and elsewhere hope to build 30-40 m ground-based telescopes with state-of-the-art coronagraphs, and Broge was optimistic that Proxima Centauri b can be studied in this way.

Direct imaging of Earth-like planets around Sun-like stars

The ultimate goal in the astronomical search for life is to look for Earth-like planets orbiting Sun-like (F-G-K) stars. Such planets are difficult to study in transit because i) the probability of a transit is small, and ii) the planet is small compared to the star. Think of it this way: an observer looking at the Sun from a great distance would have only a 0.5 percent chance of seeing the Earth transit. That means that we would need to look at ~200 Sun-like stars to find one that had a transiting Earth-like planet, even if every one of them had such a planet going around it. Or, to say this another way, most of the nearby stars probably *do* have planets (based on Kepler), but they remain invisible to us because the plane of their orbit is not within our line of sight. We can only observe such planets by using direct imaging. And, for an Earth-like planet around a Sun-like star, the *contrast ratio* (relative brightness) between the star and the planet is 10^{10}, i.e., the star is 10 billion times brighter. We don't think that we can do this level of coronagraphy from the ground; rather, we need a big, direct imaging telescope up in space.

The good news is that NASA is once again studying such telescopes. (I was involved in such a study 12 years ago for TPF-C, Terrestrial Planet Finder-Coronagraph, but the project was cancelled after only 6 months.) At the Biosignatures Workshop, Shawn Domagal-Goldman from NASA's Goddard Space Flight Center talked about two possible designs for such a telescope. The Habitable Planets Explorer (HabEx) would be a 4-to-6 m diameter telescope designed specifically for planet-finding. The Large UltraViolet-Optical-InfraRed space telescope (LUVOIR) would be a 9-to-15 m diameter general purpose telescope that could also do exoplanets. Both telescopes would be positioned at the Earth-Sun L2 Lagrange point, where JWST is slated to operate. It is my great hope to have a telescope fly while I am still around to see it.

Remote detection of life as we don't know it

For completeness, I will briefly mention the fourth quadrant of the search for extraterrestrial life: searching remotely for life as we don't know it. This quadrant is filled in with a '?' in Fig. 1, because it is not particularly well-defined. Sara Seager at MIT and her colleague William Bains have speculated in the literature about rocky planets with H_2-rich atmospheres in which ammonia, NH_3, is a byproduct of photosynthesis. They have termed such planets "Haber-worlds". Whether or not such planets might exist is unknown. We invited Bains to give a talk at the Biosignatures workshop, though, simply because we did not want to be exclusionary. I personally would not optimize a space telescope to look for such planets. However, if we had a telescope like HabEx or LUVOIR and were using it to make observations, I would agree that one should not ignore the possibility of such planets. With a good direct-imaging telescope, we will simply look at all the nearby planetary systems and see what is there. With luck, we may even find evidence for life. But, in any case, we will learn whether Earth is a special place in the galaxy, or whether Earth-like planets abound. Sara Seager, whom I just defamed earlier in this paragraph, is quite eloquent when she speaks of this search. She calls it 'the second Copernican revolution'. I agree with her perspective. It is within our power, at this time, to make some of the greatest astronomical discoveries ever. I hope that we can find the scientific and political will to make it happen.

With that, I conclude my testimony and I would be happy to address any questions you may have. Thank you, Chairman Smith and Committee Members, for your attention.

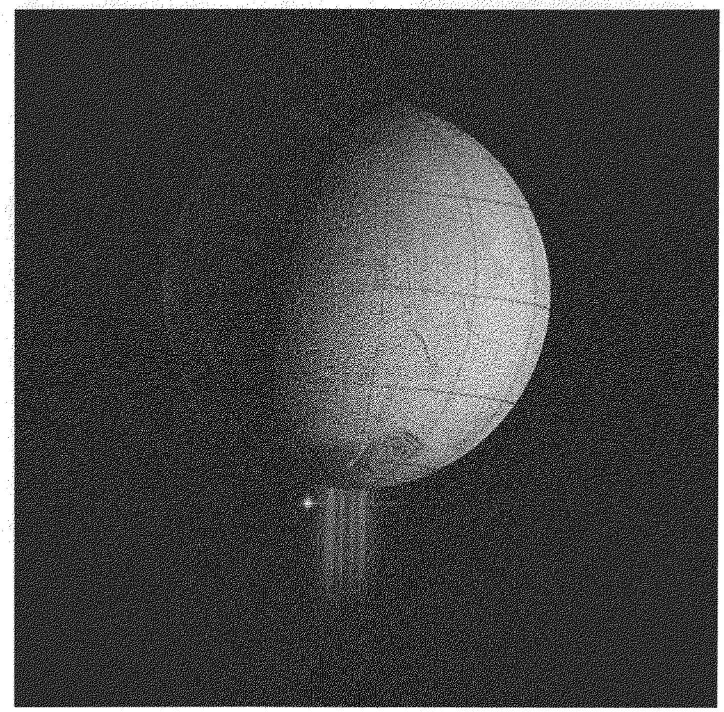
Saturn's moon Enceladus

- Methanogenesis:

$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O$$

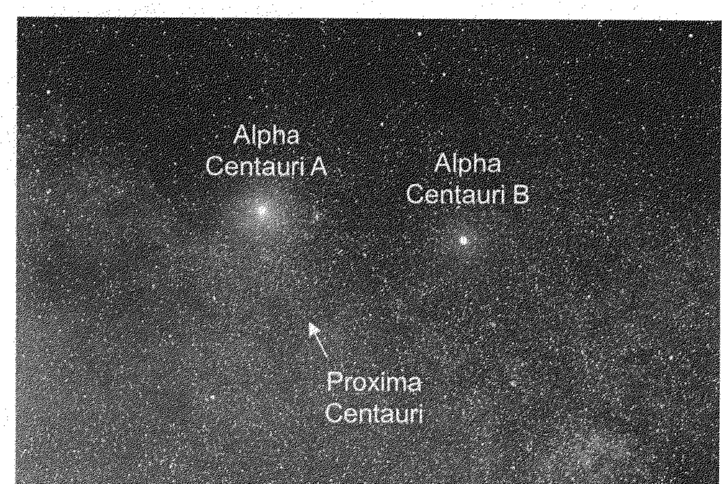
- Cassini has measured all four of these gases within Enceladus' plume

$\Rightarrow$ there is plenty of chemical *free energy* to support life in the moon's surbsurface ocean



Proxima Centauri b

- Proxima Centauri is the closest star to Earth, ~4 light years distant
  - Late M star: 0.12 M_{Sun}
  - Part of the Alpha Centauri triple star system
- The planet, Proxima Centauri b, has a minimum mass ~1.3 times that of Earth



Proxima Centauri is the small red dot within the red circle. It is too faint to be seen with the naked eye

James F. Kasting -- Biographical sketch

James Kasting is an Evan Pugh Professor at Penn State University, where he holds joint appointments in the Departments of Geosciences and Meteorology. He earned an undergraduate degree in Chemistry and Physics from Harvard University in 1975 and a Ph.D. in Atmospheric Sciences from the University of Michigan in 1979. Prior to coming to Penn State in 1988, he spent 2 years at the National Center for Atmospheric Research in Boulder, Colorado, and 7 years in the Space Science Division at NASA Ames Research Center south of San Francisco. He co-chaired the Science and Technology Working Group for NASA's proposed (but later cancelled) Terrestrial Planet Finder—Coronagraph in 2005, and he chaired NASA's Exoplanet Exploration Program Analysis Group from 2009-2011. His research focuses on the evolution of planetary atmospheres and climates and on the question of whether life might exist on planets around other stars.

Chairman SMITH. Thank you, Dr. Kasting.
And Dr. Shostak.

TESTIMONY OF DR. SETH SHOSTAK, SENIOR ASTRONOMER, SETI INSTITUTE

Dr. SHOSTAK. Chairman Smith and Members of the Committee, thank you very much. I'm going to talk about the search for intelligent life, unlike what you're likely to find under the icy crusts of Enceladus. There may be life there. There are six other places in the solar system where you might find some biology but you'll need a microscope to see it, and it won't hold up its side of the conversation.

Let me just say that in the 21st century, there are four things that I think are going to be very important that will be remembered a thousand years from now. One, we're finally understanding biology. That's going to lead to interesting questions like, you know, curing a lot of disease but also the issue of designer babies.

Second, we're going to be moving into space, something that doesn't sound so attractive if you're going to go to the moon or Mars, not great places, but if you are talking about orbiting space colonies, great. Such colonies would serve as an inoculation against self-destruction of the human race here on Earth. If we wipe ourselves out, not to worry; there's still some humans in space.

The third thing we're doing, and this is probably the most important, is inventing our successors: generalized artificial intelligence. The head of the AI operation at Stanford told me a couple years ago—I asked him will we have a machine that can write the great American novel by 2050. He looked up at me and said yes, then went back to sleep. Okay.

The fourth thing that we're going to do is find life in space, and that's philosophically important. It might be important in other ways too, but at least philosophically.

So how are we looking for life? You've heard the presentations here. There's a three-way horse race. One, we just go there and look. That's simple exploration. We go to places like Enceladus with spacecraft, grab some of the stuff being shot into space, bring it back, look at it under a microscope. Go to Mars, look around at Mars. That's where all the big money is. That's where NASA spends its money and the other space agencies around the world.

The second thing to do is build space-based telescopes that can sniff the atmospheres of planets around other stars. Dr. Kasting has already alluded to that. Again, that's hundreds of millions of dollars. It's something we can do in the next 10 years.

And the third thing we can do is what's called SETI where we try and eavesdrop on signals being broadcast by other societies that at least have technology that would allow them to do that. There is essentially no federal money for that.

All right. Let me talk a little bit about SETI. How do we go about that? What's different in the last five years. Certainly, the types of objects that we're pointing our antennas at has changed. In the old days, we would look at stars sort of like the sun because we know that stars like the sun at least have a planet where we have intelligent life, and I leave it to you to determine what's intelligence. In our field of work, if you can build a radio transmitter, you're intelligent. You can ask the guy next to you whether he can do that.

The second thing that we are doing is improving the equipment. So let me just give you an idea. The TRAPPIST–1 system has been mentioned here a couple of times. If you were in the TRAPPIST–1 system on one of those planets and you looked up in the sky, you would see, some of those other seven planets, and they would be big. They would be balls in the sky. You go out tonight, look to the east and you'll see Jupiter but it's just a point of light. Not true in TRAPPIST–1. You actually see them. Whereas it takes seven months to send a rocket to Mars, you could go from one TRAPPIST–1 world to the next during the course of a weekend.

What all this means is that there are, to begin with, more planets in the TRAPPIST–1 system that could cook up life. That means more chances to win the lottery by cooking up life, and as soon as you've done that, that life will spread to the other worlds and it will spread because meteors will slam into one planet with life and carry bacteria or whatever to the next world in just a very short period of time. So it will infect all these worlds. If there's any intelligent life in the TRAPPIST–1 system, that will have colonized essentially all these worlds too. So this could be a mini-federation of planets, if you will. This is not just another world with life; this is an ecosystem if there's any life.

We are using our Allen Telescope Array to look at the TRAPPIST–1 system, and we're using a situation in which we wait for the planets to line up and see if there's any difference in the amount of radio radiation coming our way because at that point you're looking down the communication pipeline between these planets.

Finally, let me just say something about the technology. This experiment will only succeed if we can look at about a million or so star systems. That would take thousands of years with the current technology. Thanks to improvements mostly in computers, the search is speeding up by orders of magnitude. Over the next 20 years, we will be able to look at about a million other star systems, and I'd bet everyone a cup of coffee that we'll find something. I may have to buy a lot of coffee.

Let me just conclude by saying the funding for all this is very limited. It's all private funding. There is no government money for doing this. Even though finding intelligent life would have the greatest impact on humanity, there's no federal funding, and as a consequence, the total number of people that work on this problem in the entire world is far fewer than the number of people sitting in the back row in this room.

Thank you very much.

[The prepared statement of Dr. Shostak follows:]

Written Text for Congressional Testimony

Advances in the Search for Life

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It is no longer considered foolish to argue that biology could exist on some of the trillion other planets in our galaxy. Its discovery would produce a lasting change in our perceptions, demonstrating that life is not confined to our world. We would know that biology is not some sort of miracle, but a commonplace – an ubiquitous, cosmic infection.

The discovery of *intelligence* elsewhere would be of even greater import, as we have always considered humans to be special, even the pinnacle of Creation. To learn that there are others out there – others whose cognitive abilities exceed our own – would be a discovery that would recalibrate how our species views itself. It would also have consequences that can be only vaguely gauged, in much the way that the discovery of the New World led to societal changes that were largely unpredictable at the time of its happening.

However, the search for extraterrestrial intelligence, known by the acronym SETI, has been pursued for more than a half century with no unambiguous, positive result. We haven't found conclusive proof of any intelligent (or even unintelligent) life beyond the confines of Earth. Claims that our planet is being visited by alien beings, while popular with the citizenry, are not considered credible by most scientists.

However, recent developments in both astronomy and technology are accelerating the speed of SETI searches, and it is hardly fantastic to suggest that we could find evidence of cosmic company within a few decades.

The belief that life is commonplace

For most of recorded history, there has been optimism that the heavens are filled with other beings. This was true even during the time of the classical Greeks. But hypothesis eventually yielded to observation following the invention of the telescope. For four centuries, some of the best minds in what was called "natural philosophy" claimed to espy evidence for technically advanced inhabitants on the moon and Mars. None of this was true.

Today, we have both improved instruments and greater knowledge of the cosmos. While we no longer expect to find upright, sentient aliens in our solar system, we still hear claims of possible evidence for life. In 1996, researchers at NASA and Stanford University announced that they had found fossilized microbes in a meteorite known to come from Mars. However, despite the fact that this was a major news item, most members of the astrobiology community regard this story with skepticism. Arguably, it has inclined most scientists to be cautious about announcing they have discovered life or intelligence elsewhere. But while claims are less common now, they have hardly disappeared.

As example, the dramatic changes in brightness of an object known as "Tabby's star," first found by NASA's Kepler space telescope two years ago, have been explained as conceivably due to the engineering efforts of sophisticated beings. While admitting that this is possible, most scientists think a completely natural explanation for the strange behavior of Tabby's star is more likely. Resolving this issue will be difficult, given the star's considerable distance (1500 light-years).

Tabby's star is a good example of the tendency by the public to interpret every puzzling astronomical discovery as possibly the consequence of intelligent activity. Fast Radio Bursters (FRB's), first observed approximately a decade ago, are short, enormously powerful flashes of light and radio waves coming from the sky. Roughly twenty FRB's have been seen, but their nature and workings are mysterious. Could they be alien signals? At least one has been traced to a galaxy several billion light-years distant, and if it is really due to extraterrestrial activity, then the society that produces it wields (or perhaps one should say, wielded) an energy source enormously beyond anything within our ken.

Despite the excitement of these deep space phenomena, as well as other new discoveries that might betray biology within our solar system (such as the intriguing ices being spewed into space from the Saturnian moon Enceladus), the fact remains that no certain evidence for life – dead or alive, microscopic or macroscopic – has ever been found.

Nonetheless, two high-ranking scientists at NASA have opined that we will trip across evidence for extraterrestrial biology within two decades. The present author has argued that a similar timescale applies to the detection of intelligence.

Why are researchers optimistic about the chances for discovering life so soon – even intelligent life?

One reason is the very recent evidence that planets and moons suitable for biology are bewilderingly common. One of the stunning conclusions from the data collected by the Kepler telescope is that the overwhelming majority of stars are orbited by planets. Indeed, we can now confidently state that there are roughly a trillion planets in the Milky Way galaxy, and the most common type are those that are comparable in size to the Earth. The Hubble telescope has shown us that two trillion *other* galaxies lie within the observable universe. Thus, the total number of planets within our purview is greater than the number of grains of dry sand on all Earth's beaches. The number of moons will be larger still, a fact of some importance, as moons are also possible habitats for life.

The inevitable implication of the above is that if biology is limited to Earth, then our planet is a miracle. Experience has cautioned scientists against ascribing observed phenomena to miracles.

Of course, an abundance of life does not necessarily imply an abundance of sentient life. Some biologists have argued that, while microbial life might, indeed, be widespread, intelligence could be exceedingly rare. However, given the daunting number of potential habitats, coupled with the fact that most stars are billions of years older than our Sun (allowing ample time for evolutionary processes to produce complex organisms), such pessimism seems unwarranted.

Searching for life

Leaving aside scientifically questionable claims that extraterrestrials are visiting Earth, there are three main schemes currently used for discovering extraterrestrial biology:

1. Find it *in situ* by, for example, sending robot spacecraft to investigate promising sites on Mars or gather samples from ice geysers that spray from two moons of Jupiter and Saturn. These are experiments that are possible for NASA or others to do in the coming decade.

2. Measure the secondary effects of biology in the atmospheres of nearby exoplanets (planets around other stars). The detection of abundant oxygen or methane could tip off researchers to the presence of biology on other worlds. NASA's new James Webb space telescope might be capable of making this type of measurement for the nearer exoplanets, as will very large, ground-based optical telescopes planned for operation within ten years (e.g., the Thirty Meter Telescope).

3. Detect radio or optical (visible light) signals from other star systems. Such signals would indicate the presence of technically accomplished inhabitants. This is the approach used by most SETI researchers.

We consider this third approach, and the search for intelligence, in what follows.

While the first SETI experiment was conducted nearly six decades ago, neither it nor any of its successors has captured a signal that has been confirmed as having an artificial, extraterrestrial origin. Despite this seemingly disappointing track record, it would be a mistake to ascribe this to a lack of prey. Because of the need to examine both a large number of stars, over a wide swath of the radio spectrum (generally at microwave frequencies, where the universe is relatively quiet), these experiments are slow. They go through their observing lists at a rate that's typically a handful of star systems each day.

To put that in context, if we conjecture that there are 100 thousand signaling societies in our galaxy, then we will have to scrutinize roughly one million star systems before detecting a transmission. This is approximately ten times the total sample of all SETI experiments undertaken since 1960.

However, thanks to rapid advances in computing technology, SETI experiments are becoming faster. In the past two decades, the receivers used for such work have improved to the point where they can instantaneously seek signals over many tens of millions of radio channels. In the next decade, this will become hundreds of millions, or even a billion.

This stunning advance in capability means that reconnaissance of the myriad star systems of the galaxy will become far faster, and within twenty years it's fully possible that the requisite examination of a million star systems will occur. It is not the speed of our computers that facilitates this promise, but the rapid rate of its increase.

As example, the SETI Institute is currently using its own antennas – the Allen Telescope Array, situated in the Cascade Mountains of Northern California – to search 20,000 nearby, red dwarf star systems for signals, and the Breakthrough Listen initiative of the University of California intends to eventually reconnoiter a million star systems. These are both searches that are orders-of-magnitude more ambitious than previous efforts.

In addition, the Allen Telescope Array has been used to examine unusual objects, such as Tabby's star, mentioned above, as well as the TRAPPIST 1 system: a red dwarf star known to have seven orbiting planets all similar in size to Earth.

TRAPPIST 1 is an especially interesting system, both because of its properties and the opportunity it affords for a "smarter" SETI search. At least three (and perhaps more) of the seven planets in this system could have environments conducive to biology. That means that if life has sprung up on any of these worlds, it has undoubtedly migrated to some (or all) of the others. Even bacteria could manage a pilgrimage from one planet to another given the fact that these worlds are so close together (typically separated by a million miles, or only 3 percent the distance between Earth and Mars). Microbes could hitchhike on rock kicked up by incoming meteors, and infect neighboring worlds. If there's intelligence on any of these planets, it's safe to say that it will eventually carpet most, if not all, of the remainder. TRAPPIST 1 offers not only multiple worlds on which biology could arise, but the opportunity for a multi-planet ecosystem.

This latter possibility has inspired an unusual experiment. When two of the TRAPPIST 1 planets are known to line up as seen from Earth, then the Allen Telescope Array is switched on to observe the system. In this arrangement, we are looking down the planet-to-planet communication channel between these worlds. Any rise in cosmic static would indicate the presence of intelligence.

This is the type of experiment that, even five years ago, could not have been done – simply because we lacked the astronomical knowledge that makes it feasible.

In addition, the SETI Institute has begun a project to search for very short flashes of laser light coming from the stars. What distinguishes this effort from other so-called "optical SETI" experiments is that, for relatively little investment, it should be possible to search the entire night sky, all the time, albeit at relatively low sensitivity. This is a very new development, and one that might permit the detection of societies that are not relentlessly targeting Earth with signals.

Funding and public benefit

No one knows when – or even if – we will find life beyond Earth. As noted, most researchers, including those at NASA, think that such a discovery is imminent, within the lifetime of today's millennials.

However, discovery is dependent on funding, and for SETI this is a crippling bottleneck. Until the early 1990s, there was an ambitious NASA SETI effort, conducted at the Ames Research Center and the Jet Propulsion Laboratory. The annual budget, at its peak, was $10 million. Today, excepting a grant to the University of California at Berkeley SETI group by Russian billionaire Yuri Milner, all SETI is funded by donations from the American public. While NASA's budget for solar system exploration is about $1.5 billion, the efforts by the SETI Institute to find sentient life is funded at a level that is two thousand times less. This is despite the considerable public and academic interest in the question being addressed. The total number of people world-wide engaged in SETI is no more than twenty.

The discovery of intelligent life would undoubtedly have a profound impact on society, and indeed, numerous scholarly panels and publications have attempted to gauge what this might be. An informal poll of science journalists by the present author asking how they would rate such a discovery resulted in a unanimous response that this would be "the biggest news story of all time." This despite the fact that whatever intelligence is found will likely be hundreds of light-years distant or more. Conversation, in any normal sense, will not be possible; the communication will be effectively one-way. That needn't diminish its appeal: the writings of the classical Greeks and Romans have taken millennia to reach us. They are still interesting.

But there are benefits to SETI that are tangible and worthy even before, or without, a discovery. Young people are invariably captivated by "aliens" – an interest similar to, and as universal as, their fascination with dinosaurs. Searching for intelligence in space is an effective hook to stimulate their interest in science. This is not hyperbole. The National Academy of Sciences has recognized that a large fraction of those who eventually choose science as a career have done so because of the fictional depiction of science in film and on TV. And much of this programming centers on the existence of beings elsewhere.

Aside from its appeal to young people, the subject of SETI strongly interests the general public. Unlike much modern research, the ideas of SETI are easily comprehended by the non-specialist. It is accessible in a way that other projects are not. The hunt for the Higgs boson was important and expensive. But few people understood the quest or its significance.

SETI is exploration. Unlike much science, its premise can't be falsified. We can't prove that the aliens aren't out there. Like Captain James Cook, we sail the seas of the cosmos with the hope of discovering something new. Despite this uncertainty, SETI has benefits that are tangible and worthy before – or even without – a discovered signal: namely, interesting the public in science, and schooling them in scientific thinking.

The United States exists because of exploration. We, of all nations, should know its value.

Biographical Sketch: Seth Shostak

Seth is the Senior Astronomer at the SETI Institute, in Mountain View, California. He has an undergraduate degree in physics from Princeton University, and a doctorate in astronomy from the California Institute of Technology. For much of his career, Seth conducted radio astronomy research on galaxies, and has published approximately sixty papers in professional journals.

He has written more than five hundred popular magazine, newspaper and Web articles on various topics in astronomy, technology, film and television. He lectures on astronomy, and gives approximately 60 presentations annually. For a decade, he chaired the International Academy of Astronautics' SETI Permanent Committee.

Every week he hosts the SETI Institute's one-hour science radio show, "Big Picture Science"

Seth has written, edited and contributed to a half dozen books. His most recent tome is *Confessions of an Alien Hunter: A Scientist's Search for Extraterrestrial Intelligence* (National Geographic), and he is co-author of a college textbook on astrobiology.

Chairman SMITH. Thank you, Dr. Shostak. Thank you all for your fascinating testimony, and I'll recognize myself for questions.

And Dr. Shostak, let me address first a comment and then a question to you. The comment is this. I want to, I think for the first time publicly, thank you for exposing me about 2 decades ago to SETI's methods of looking for the search for extraterrestrial intelligence when we spent what seemed like a long night at Arecibo, but that was my first real exposure, and it sort of set me on the track to be continually interested in the subject, so thank you for that.

A couple of questions. One is, just to read from part of your written testimony. "if we conjecture that there are 100 thousand signaling societies in our galaxy, then we will have to scrutinize roughly one million star systems before detecting a transmission. This is approximately ten times the total sample of all SETI experiments undertaken since 1960." So we're just beginning the process. We have a long ways to go.

You mentioned all the different ways we might search for extraterrestrial intelligence. What do you think is the best current method being used, is it radio, is it laser? What might it be? And what do you recommend?

Dr. SHOSTAK. Well, it's obviously hard to forecast what to do to succeed. It would be like asking Captain Jim Cook, two weeks out of England, what part of the Pacific is best to search for new islands. Obviously we don't know. But the radio searches are following a trajectory in terms of improvement. That's very easy to predict because it follows Moore's law. It just follows computer technology. And so we know that over the course of the next two decades, radio SETI will get at least 100 times faster and maybe more.

So I have a dog in this fight. I seem to think that that is a good way, but I have to say, we're also developing schemes for looking for flashing laser lights in the sky. If a laser—if some society out there is aiming a laser beam at us a thousandth of a second long once every two weeks. nobody on Earth would ever know. We wouldn't know that. And it's worth looking for that because indeed, except for the transmissions we've been broadcasting into space since the second World War, there's no way that the aliens could know we're here. If they're more than 70 light-years away, they don't know that Homo sapiens exist. So maybe they just ping us intermittently to see if anybody's home.

Chairman SMITH. Thank you, Dr. Shostak.

Dr. Zurbuchen, let me ask you the next question, which is, the Authorization Act that we just signed into law last month directs NASA to search for life in the universe, any form, any kind. How will NASA implement the directive in the NASA Authorization bill?

Dr. ZURBUCHEN. Thanks so much for the question. First of all, there's a number—you should know that with me at the leadership of the Science Mission Directorate, this is one of the top three priorities that we're focused on, so it's a high-level priority that we used to integrate research across disciplines. So the way we'll look at it is an interdisciplinary fashion, first of all. The second one is to recognize that we already have a series of missions that are in development. We've talked about them here. Trying to really deploy them in a strategic fashion.

We're looking of course at the Academy's input and prioritization to help us with that because we think the Academy is exactly the right, like you directed, exactly the right voice for us to really exploit these assets the right way. Also, as we go forward and look at decadal guidance from other disciplines as they come forward, we expect that we'll also develop perhaps new technologies, new assets that will help in that search.

Chairman SMITH. Okay. Thank you.

Dr. Burgasser, you mentioned that the most common type of star in our galaxy are the red dwarves, which you study, and those are fascinating slides you put up. What is the likelihood that we will find life near a red dwarf star?

Dr. BURGASSER. That is a very challenging question. I can only address that these red dwarf stars have a lot going for them in terms of being able to search for life on planets around them. They are the most numerous. They're also the nearest stars to our sun. It turns out that there are more terrestrial planets per Mdwarf than sun-like star. There're about terrestrial planets on average for all these low-mass stars. And the ability to measure their atmospheres is enhanced by their small sizes, the stars' small sizes.

Now, there are things that are not going for small stars. These planets are very close to their stars so they are tidally locked, and we are still trying to understand what effect that could have on the climates of these planets, and they're also exposed to higher magnetic storms, the kind of magnetic storms we get from the sun but actually much more powerful because they are closer to their stars, and that may or may not have positive or negative implications for development of life on these planets.

So these are active questions because we've only just started finding these planets. We are really approaching this from both theoretical and observational perspectives to understand what we might expect to find, but of course, the best thing to do is actually find this evidence and then we can provide an answer.

Chairman SMITH. And go from there.

Dr. BURGASSER. Yeah.

Chairman SMITH. Thank you.

Let me squeeze in a last question maybe directed to Dr. Zurbuchen and also Dr. Shostak. Should NASA consider—and I think there's appropriate language in that authorization bill—should NASA consider contracting out with organizations that might be searching for extraterrestrial intelligence?

Dr. SHOSTAK. I think my answer's a foregone conclusion.

Chairman SMITH. Yes.

Dr. SHOSTAK. Yes. No, I think so, and for several reasons. One, of course it would be more interesting to find it, I think, than—with all deference to the astrobiologists here, I think it would be very interesting, particularly to the public. The public's very interested in life but mostly in the intelligent variety. I make that statement without numbers here but I think that's true. And the other thing is, it would be philosophically very consequential. There are other possible sequelae. You could indeed maybe understand something they're saying in which case you're in touch with a society far more advanced than ours. I don't know what the consequences of that might be. I don't even think that it's very likely we would understand anything. But simply to know you're not the only kid on the block I think is—that's exploration that I think is worth doing.

Chairman SMITH. Thank you, Dr. Shostak.

The gentlewoman from Texas, the Ranking Member, Ms. Johnson, is recognized for her questions.

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

I guess I will point this question to each of the panel members. How important do you think the sustained federal support for research of core science disciplines such as biology, geology, chemistry, physics and astronomy to the success of interdisciplinary fields of astrobiology, and to what extent would the budget cuts have on the impact of this research that's in progress now for search for life? What are the challenges to us?

Dr. ZURBUCHEN. Let me answer the first part of your question of just how important it is, and I really do believe that to answer this question, is there life out there, is really a complex—it's not a yes-no kind of answer. The way to think about that is not that it's—it's really opening up a new areas of research with entirely new research questions that we've never seen. The way we do answer these questions, each one of those questions, whether it's hydrogen and the plumes of Enceladus relates to fundamental science that is underlying that, so how important is it to have this fundamental science is essential. It's the tools we use in every one of those questions to actually unlock the unknown.

Dr. BURGASSER. And so I will echo your comment that this is a fundamentally interdisciplinary nature. I'm actually teaching a writing course. Let me give out a shout-out to my students who have to watch this next week. And we bring together areas across the science disciplines but also beyond the science disciplines. Congressman Bera mentioned that this is a disruptive question that we're asking, are we alone, and so it doesn't just touch on science but it also touches on philosophy, legal issues, all kinds of issues. So at its core, we really need to have a very broad-based knowledge sort of system to understand both the question and also when we answer that question, what does it mean for humanity.

Dr. KASTING. If I could just add that of course you need the support of the basic sciences at the basic level but we're also seeing the need for more coordination between planetary science and astronomy because those used to be—they are two separate divisions within NASA but with exoplanets, we share a common goal of understanding those planets, and so, you know, I've been happy to see that the two divisions in NASA have talking to each other, and I think that's very important in making progress in the future.

Dr. SHOSTAK. Well, I support what has been said here. Clearly, it is interdisciplinary, and it's also exciting science. It's also comprehensible science to Mr. and Mrs. Front Porch, if you will. If you ask your neighbor, hey, what do you think about the Europeans spending billions of dollars to find the Higgs Boson? Well, that's fundamentally important, but I doubt that they understand what it's about nor do they probably want to spend that kind of money.

I don't know. But this is exploration when you talk about astrobiology. It's something everybody understands right away. It's also exciting science, and not to do it, I mean, it would be like if you're a European country in 1500 and somebody says do you think it's worth investing in some ships and some crews and send them around the world and see if we can map the globe? Obviously it was worthwhile.

Ms. JOHNSON. Thanks to all of you.

Of course, research to me is the door to the future. My concern is that each year we go through whether we're going to cut back on NASA research, and I wonder whether this will have an impact to focus more strongly on this. I don't want an either-or. But it seems that to do another is to neglect the other. How do you think we can continue forth with both bodies of research, and what is the importance?

Dr. BURGASSER. I'll take a stab at that. You know, I think we have to listen to our citizenry and understand that these are questions that excite, inspire and drive interest not just in astronomy but across STEM fields and keeps us competitive at the world stage, and so an investment in NASA is going to have incredible returns down the road across all fields of technology, of biomedical science, of new materials, and you know, I leave it up to your esteemed colleagues to decide where these budgets land.

Ms. JOHNSON. It's dangerous.

Dr. BURGASSER. But it is certainly critically important to realize that this is investment in our future on many levels.

Ms. JOHNSON. Thank you very much. We've learned so much, and I want to see it keep going, but I am concerned. Thank you.

Chairman SMITH. Thank you, Ms. Johnson.

And the gentleman from Louisiana, Mr. Higgins, is recognized for questions.

Mr. HIGGINS. Thank you, Mr. Chairman.

Dr. Shostak, it's been stated for decades that some species of cetaceans—whales and dolphins—are recognized for their intelligence. Would you agree with that general assessment?

Dr. SHOSTAK. Yes, clearly they have a higher encephalization quotient. That's a lot of Greek, but what it means is their brain volume relative to their body volume is higher than any other critters on this planet other than our simian friends and ourselves. So by that measure, they are clever. They also can recognize themselves in a mirror. They know that when they look in a mirror, they're seeing themselves, something your dog can't do.

Mr. HIGGINS. Is it generally accepted that these creatures have a means by which to communicate with each other?

Dr. SHOSTAK. There are people that think that. I'm not one of them. I knew John Lilly a little bit, and Gerrit Verschuur is another guy who thinks that the cetaceans can communicate by ESP. I think that there's a great experiment being run that disproves the notion of ESP. It's called Las Vegas.

Mr. HIGGINS. I would agree with you there.

But they do vocalize, do they not?

Dr. SHOSTAK. They do, and in fact, a sort of a statistical analysis of the sounds they make shows or at least seems to indicate that it's a language. It's not just barking, if you will. So yes, they are clever, they are quite clever, but you will note that their level of technology leaves something to be desired. That may be partly a consequence of living underwater where it's hard to smelt metals and so forth and so on. But I don't think that the cetaceans are comparable to humans.

Mr. HIGGINS. I bring this up because a research scientist by the name of Lawrence Doyle at the SETI Institute has studied information theory and patterns in animal communication as a means of understanding how to detect signals from the noise we hear from space, and I'd like your comment on that. Within your comment is my own personal consideration that should intelligent life ever be discovered, whether or not that's, you know, a realistic perspective is subject to debate, I'm sure, but should intelligent life in the cosmos ever be discovered, if for decades we've been unable to communicate with dolphins and whales, how should we ever expect to communicate with intelligent life if it would be discovered across the cosmos, and how does that relate to Lawrence Doyle's research?

Dr. SHOSTAK. Well, I certainly agree that the fact that we can't communicate with any other species on this planet may indeed incline you to think that we would never be able to find it elsewhere. I think what it might show is that we might not understand anything being sent but, you know, the way we do this experiment is not by listening for patterns in any signals, messages, such as, "here's the value of pi," or "here's the Fibonacci series" (if you're a Dan Brown fan). None of that. We are simply looking at the nature of the signal, the kind of signal that transmitters make without regard to the message. The message would be much, much harder to find in any case, the bits such things as what language they use if they use any language, how they've encoded their information, the things that separate whale communication, for example, from human communication, all that is sort of, if you will, literally below the radar. So what we are doing is just trying to and find the technology they use. This signal is due to a transmitter. What they're saying is not something we'll know right away, and maybe never.

Mr. HIGGINS. And that would describe Lawrence Doyle's work?

Dr. SHOSTAK. He's interested in finding out if you have a big brain, do you start using language. At what point do you start using language? I have to say that he has found statistical indications that the dolphins are using language, also in many other species he claims, even in ants. I have to say I've never been impressed by ants' intelligence, but on the other hand, maybe they're not impressed by mine.

Mr. HIGGINS. I think that's an excellent time to yield back, Mr. Chairman.

Chairman SMITH. Thank you, Mr. Higgins.

And the gentleman from California, Mr. Bera, is recognized.

Mr. BERA. Thank you, Mr. Chairman. This is a great hearing, right? I mean, it is a seminal question, particularly again if we want to stimulate our next generation to really, you know, get interested in science. I mean, it's very easily understandable. You suggest that it's not Higgs Boson, it's "are we alone?", that search for life which any student can grasp and any individual can grasp, and it opens up philosophy, it opens up, you know, humanity, et cetera.

You know, Dr. Shostak, you talked about three different methods: direct exploration, space-based telescopes or looking for signals. I don't think it's either-or, right? These are all complementary modalities that work off of each other and feed into the body of knowledge. Given the vastness of space—and my question would be, you know, we don't have the funding to do everything and look at every piece of information that's coming in so some of—you know, with the internet and the interconnectedness of the world now is that citizen scientist, those citizen astronomers. What are some thoughts and ideas of how NASA and other agencies including SETI can use that, you know, that mass of humanity in a strategic way to get folks to look for those signals or look at the vastness of space but then also to encourage our young people, you know, so classrooms of students might actually be part of this search for life.

We'll start with——

Dr. ZURBUCHEN. So I agree with your notion entirely and also that there are opportunities and that we can do that. You know, one of the coolest things right now when I was doing my Ph.D. on a different continent. My computer at night was working for his organization with SETI at home, right, because my computer was tied in, many of my colleagues basically gave our CPU power away for that. I think right now we have many opportunities. Whenever Juno flies by Jupiter, you know, there's thousands of people the next day taking the new imagery, you know, of all ages, you know, children of all ages taking the imagery with wonder and turning art—turning them into art, really analyzing them, sometimes actually finding exciting science in doing so. So at NASA we're really excited about these citizen science type of projects, and we actively look for collaborations in areas also we're currently throughout the decadal process and otherwise our funding emphasis is not high. You should know that last week I was in a meeting I think with you, Dr. Shostak. We were in a room, you know, where we talked about all aspects of search for life, and every time we come back, we want to, you know—as we make progress, we look at it again are we doing—putting the money at the right place. The reason we're so excited about search for life right now is we're really driving up the S curve but the slope is enormous right now of the progress we're making, and this is one of the most fruitful, really civilization-scale questions we can address, so that's why we're so excited.

Mr. BERA. Dr. Burgasser?

Dr. BURGASSER. Yeah, thank you for asking that question. I think it is important to recognize that the decadal process in this is one of the ways that we as scientists, a very diverse group of scientists, come together and identify what are the main ways that we can address some of these outstanding questions, and that's an important process because it's a competitive process but it's also a consensual process and so we kind of come together on this.

I wanted to touch on your engagement with community in terms of the science itself, and certainly the citizen science programs such as Planet Hunters and Exoplanet Explorers, Background World, SETI at Home have engaged a lot of the public to this work, and they have contributed to discoveries, and that's one of the amazing accessibility parts of this kind of research.

But I should also say that the importance of this work being publicly funded also means that the data and the research that we produce is immediately available to the public, and I have been able to work with a diverse group of students from minority-serving schools, from low-funded schools in San Diego, and researchers across the world to actually work on the raw data to find these planets, and so that's one of the ways that we really engage the public at large is that they can actually really do the research because they are using data that's funded by the public.

Mr. BERA. Dr. Kasting?

Dr. KASTING. I think it's been great that the public has been able to get directly involved in SETI, and I think that's generated a lot of interest. SETI—as I said in my written testimony, SETI got started before the search for simple life because the technology is actually simpler than the search for simple life, and you know, it's very—it's more difficult to get the general public directly involved in the search for simple life because you need big space-based telescopes and big ground-based telescopes so there's a role for the public but there's also a role for government in the search for life.

Mr. BERA. So it looks like I'm out of time, but Dr. Shostak, if you want——

Chairman SMITH. Thank you.

Dr. SHOSTAK. Oh, just one thing. First, I'm slightly embarrassed. SETI at Home is not our project. It's University of California-Berkeley. But here's something that hasn't been mentioned, and that is the National Academy of Sciences has recognized that a very high percentage of people who go into science go into science because of what they've seen on television and in the movies, and so they have a project, they have an office down in Irvine, California, near Hollywood, and they in fact—whenever they hear of a new film being made about space, they will bring in some scientists to try to get the science right. Personally, I don't think that makes any difference in the appeal, but the facts are that that sort of informal exposure to science has a tremendous effect.

Mr. BERA. Thank you. I'll yield back.

Chairman SMITH. Thank you, Mr. Bera.

The gentleman from Florida, Mr. Posey, is recognized for his questions.

Mr. POSEY. Thank you very much, Mr. Chairman.

Dr. Zurbuchen, we often characterize investments in basic scientific research as paying off in technical advances that will eventually impact our day-to-day lives here on Earth. Can you point to some recent examples of breakthroughs in the astrobiology field that have had that type of impact?

Dr. ZURBUCHEN. I am sure there are examples, and I will return with questions for the record. I can give you examples that I encountered just recently in astrophysics in general. For example, look at some of the mirrors that were developed for X-ray optics that relate to this research, mirrors that are of course raising incident mirrors that are done at Marshall in Alabama, and these mirrors are subject of tremendous interest from the biomedical space because of the fact that of course we want to focus X-rays also in medical application and spin-offs of a variety of, you know, characters of foci can be formed with that. They're in negotiations right now so there's not a big company right there.

But we have ample ones of these, you know, stories that are forming around our research, and that's also why we're so excited about—you know, I've been a part of hundreds of start-ups in my previous job as an innovation leader at the university I worked before, and I really believe in it, but I will get back on good examples that are recent and are related to this.

Mr. POSEY. Thank you.

Any of the others care to comment on what you see coming from research in the next three to five years?

Dr. KASTING. Could I just take a stab at that? I don't actually know practical things that come out in the next three to five years but my colleague Sara Seiger at MIT, who's an astronomer, sometimes calls the search for life the second Copernican revolution, and so Copernicus figured out that the Earth goes around the sun rather than vice versa. We are looking to see whether we're alone in the universe and whether life is common, and you know, I'm not sure there were practical things at the time that came out of the Copernican revolution but nevertheless, it changed mankind, and so could this search.

Dr. SHOSTAK. I might also point out in 1920 if you talked to physicists that were worrying about quantum mechanics and they themselves would have said there's absolutely no practical application of any of this, and now everybody carries quantum mechanics around in their pockets.

Mr. POSEY. You know, we just had the March for Science all over the world, and of course, a lot of people think there's only one answer to all scientists and all science, and that's whatever they think, and I remind them that until Galileo, 100 percent of the world's scientists swore the Earth was flat and, you know, you have to ask those questions. You have to question what some consider as fact.

Thank you, Mr. Chairman.

Chairman SMITH. Thank you, Mr. Posey.

And the gentleman from Virginia, Mr. Beyer, is recognized.

Mr. BEYER. Thank you. Mr. Chairman, thank you for holding this very bipartisan hearing. It's very exciting. And thank you all for being here.

Dr. Shostak, I was reading about METI rather than SETI, the Messaging to Extraterrestrial Intelligence, and one of the things they said was, they defined—they said that we were not a communicative civilization because we don't practice such activities as purposeful and regular transmission of interstellar messages. Should we be a communicative civilization?

Dr. SHOSTAK. Well, that's really up to you. I mean, there are people who think that we ought to take the initiative, send signals into space and see what comes back, if anything. I point out that this has been done in the past, mostly as demo experiments. You know, even the records on the Voyager spacecraft and the plaques on the Pioneer spacecraft are designed in case any Klingons ever pick these things up, which they never will, but, you know, they get a greeting card from Earth.

I don't agree with those who think that this would be dangerous. There are people who say that. Even Stephen Hawking has made that comment. Because you obviously tip of the aliens that we're here, and who knows what they really are like. Obviously we don't know anything about alien sociology, and maybe they would just come to Earth and incinerate the planet on a bet. I don't worry about that personally, but you might say that's not good enough.

Let me simply point out that we have been transmitting into space willy-nilly since the war, and it's mostly TV and FM radio, it's mostly radar. It's mostly radar. So if you're paranoid and you're worried about this, if you think maybe it's not a good idea to let anybody who's out there know that we're here, then you better be prepared to shut down the radars at Reagan Airport, and I don't think you want to do that.

Mr. BEYER. You mentioned the 70 light-years as sort of the—is that because that's when radar and——

Dr. SHOSTAK. Yes, and also FM radio, but yes, radar, television and radar are the things that go out—you know, they go right through the ionosphere, and radar transmitters tend to be very powerful. If you were looking at the Earth from one of these nearby planets that we've talked about here and you had a big antenna, you know, as big as this building, you could pick up our radars.

Mr. BEYER. You mentioned a number of times the philosophical and theological consequences of discovering life, and obviously there's lots and lots in the science fiction literature and films and stuff about how people react, overreact, go crazy. Are there philosophers or theologians thinking about this, writing about it trying to anticipate what it would be like?

Dr. SHOSTAK. There are. There's a lot of research. And normally what they do is, try and look for an historical precedent for this. I guess it's sort of lawyerly to do that. And they say okay, what in history has happened that would give us some clue as to what the public's reaction or organized religion's reaction would be. But there is really no very good precedent for this.

When I tell people at cocktail parties—not that I get invited to many—but if I tell people what I do for a living, they'll frequently ask well, if you found a signal, you wouldn't tell us, the government would shut you down, right? And I said the government doesn't even know what we're doing. I don't think they would shut us down. We've gotten false alarms in the past. There was no interest by the government. My mom didn't even call. Nobody was interested, only the New York Times. They were interested.

But they think that the public couldn't handle this news. I think that that is totally false. If you were to pick up a newspaper—you won't do that—open your browser tomorrow and find news that we'd found a signal coming from 800 light-years away, I doubt that you would say I'm not going to work today, I'm going to riot in the streets.

Mr. BEYER. We ran SETI at Home for years with my kids and all the different computers, and now we're looking for Riemann prime numbers, I guess, because the SETI thing has shut down, which——

Dr. SHOSTAK. We could always use more prime numbers.

Mr. BEYER. Yeah, we haven't found any prime numbers yet either.

I have talked to scientists, though, who say we've been looking for so long, you mentioned 100 million planets, and they almost argue that because we haven't heard anything that there must be nothing there.

Dr. SHOSTAK. No, that's a false argument. Look, that's like going to Africa, looking for big mammals with long noses that can pick up peanuts, and quitting after you've examined one city block's worth of real estate. That's equivalent to the fraction of our own galaxy that we've looked at. There're roughly a trillion planets in our galaxy. There're two trillion other galaxies we can see, each with a trillion planets. To say oh, well, it's all sterile is a bit self-centered.

Mr. BEYER. Dr. Kasting, in looking at Enceladus's plume, how fast are the gases escaping? Is there any—is this something that will go on for millions of years?

Dr. KASTING. My understanding is that plume will keep going. You know, there are four stripes on Enceladus' south pole called the tiger stripes, and the plume is coming out form there. So this plume has been there for the ten years that Cassini has been up. You know, what you want to do is actually try to encounter that plume at slower velocities. It's a spacecraft moving fast through it that makes it difficult to measure. So it would be nice to go back and go through that plume. I think it will be there and go through it more slowly.

Mr. BEYER. And very quickly, I'm familiar with the binary stars where the one rotates around the other. When you get to the triple star system with Alpha Centauri, are they—what's the planetary motion or the star motion that goes along with three of them?

Dr. KASTING. The two bright ones, Alpha and Beta Centauri, are close together and orbit pretty quickly. Proxima Centauri, the M star which has the planet around it, is far away and it's actually not even entirely certain that it's gravitationally bound.

Mr. BEYER. Okay. Interesting. Thank you very much, Mr. Chairman.

Chairman SMITH. Thank you, Mr. Beyer.

The gentleman from Oklahoma, Mr. Lucas, is recognized.

Mr. LUCAS. Thank you, Mr. Chairman, and I agree with my colleagues. This is a fascinating topic. It's caught the attention of our constituents back home, and from that perspective, let me ask the panel: we've invested on the federal level, whether it was Hubble before and the first generation of space telescopes that caught the public's imagination or the money we're spending on James Webb, our European friends and a number of folks in Chile and a variety of other places spent substantial monies that can be used in the exoplanet search work. Visit with me for a moment about the technical requirements if we are successful in finding a blip, a squeak, a whatever, how we go forward with the next generation, what is required to go to the next generation. Do we ultimately have to tie every telescope that's on the surface of the planet together computer-wise to create that field to observe from? Where do we go in the next generation, which if we encounter something that's defined as a likely, the public will become very enthusiastic for?

Dr. ZURBUCHEN. It's my belief that most of the technologies that we're going to deploy to answer this question have not yet been invented. I really believe that what's going to happen as we go forward and look, for example, at microbial life in the solar system or we look at exoplanets and look at the first emissions of atmospheres using James Webb and other telescopes we're building now, there's innovators right now that are developing next-generation highly sensitive spectroscopy type of tools that even within a few years will be proposed to one of our announcements of opportunity at NASA or elsewhere, and really will cause that kind of rapid rush forward that is really typical of this kind of research. So for me, that's one of the amazing parts of this research is that it causes so much innovation.

You know, the first planet around another star was announced in 1995, you know. It's a little bit over 20 years. Look where we are today. Look at the tools we're using today. We never knew to look at dwarves as, you know, we didn't know how, right, and so this is where kind of the motherlode is of this. So for me, it's really that progress that makes it so exciting. Yes, there will be a lot of innovation.

Dr. KASTING. Could I make a comment on that?

Mr. LUCAS. Yes.

Dr. KASTING. We've heard about James Webb Space Telescope, which is this huge, wonderful telescope that's going up next year, but James Webb will only be able to take spectra of the transiting planets, which is a small fraction of the planets out there. Most of the nearby stars, the planets don't transit. So what we really need is big, direct imaging telescopes of the same size as JWST or maybe even a little larger but specially equipped with coronagraphs or star shades to block out the light from the stars so that you can see the planets orbiting around it, and so that's my own personal interest. I think that's where we have the best chance of finding life.

Dr. SHOSTAK. In the case of intelligent life, of course, every telescope in the world would be aimed in the direction from which the signal's coming. You can be sure of that. But in terms of what's coming down the pike for instrumentation, the Europeans, mostly the Europeans are building what's called the square kilometer array, both in South Africa and western Australia, and that's an instrument that's 10 times larger than Arecibo, which is already 10 times larger than what we're using. So that kind of thing would allow us to follow up and find other signals coming from other places. Usually in astronomy, if you find one of thing, that means you're going to find a lot more rather quickly, partially because you know what you're looking for.

Mr. LUCAS. Doctor?

Dr. BURGASSER. Thank you, and I want to thank you for asking that question. I want to tack on to the technology development that we can't even anticipate at this point just the techniques that have been developed to find these planets were things that were not anticipated early on. So the Spitzer Space Telescope, which I mentioned was central for discovery in the TRAPPIST planets, when it was launched, it was not designed to do what we did with it. It was not designed to look for exoplanets and measure these transits and yet it's been one of the most successful outcomes of that mission. And so I think when you give people tools, they discover new ways to use them and ways that we may not anticipate that could actually do more with the investments in these facilities than we could have expected.

Mr. LUCAS. Thank you very much. Your comments present optimism that's very vast and it's fascinating to think that we have our echo chamber out 70 years, so to speak, light-years.

With that, Mr. Chairman, I yield back.

Chairman SMITH. Thank you, Mr. Lucas.

And the gentleman from California, Mr. Rohrabacher, is recognized.

Mr. ROHRABACHER. Let me first apologize that I came in late. As you know, we have several hearings scheduled at the same time. I will be looking at your testimony, your written testimony, and I want to thank the Chairman. We have a Chairman who's a visionary, and we're lucky to have him there to be able to touch on things like this. I might say that other chairmen that I've served under were not quite as willing to go into these type of areas because they were afraid of ridicule. I mean, you can see it—"Oh, they're out searching for aliens in outer space," and we need to have a very serious discussion on your mission and what's going on, and let me just note that I have been a long-time supporter personally of developing telescopes of deep space missions as well as astronomy in general, knowing that with astronomy we can determine truths that are happening out there that affect our knowledge even of molecular structure and how it works on the land. So I will have to tell you that they didn't have to twist my arm in order to get my support for those projects.

First of all, let me just ask this. I have a 12-year-old son, and he would just die if I did not ask this question. With what we know now and how you have now just expanded our understanding of how far reality goes out from our planet, with that in mind, here's my son now: Is time travel possible?

Dr. SHOSTAK. If you're willing to go to the future. That you can do, and you're doing it right now. Going to the past seems to violate some basic tenets of physics.

There's a book out about time travel, a new one your son may want to read, and it's—I think it's by Glike, the same guy who——

Mr. ROHRABACHER. But actually some of the things you're doing now and you're studying will give us understanding maybe 100 years from now on something that may be an incredible breakthrough for humankind like the idea that it's possible to have time travel.

Dr. SHOSTAK. Well, one should never discount the possibility of new physics that changes one's attitude, but at the moment I would bet against it.

Dr. KASTING. If I could comment, I don't know about time travel but I always thought that travel to other stars was impossible but, you know, there's a private group out in California called Breakthrough that is studying Project Starshot. They want to send a spacecraft to Alpha Centauri and so that's something that I never thought was going to happen but, you know, it's not impossible.

Mr. ROHRABACHER. Not impossible?

Dr. BURGASSER. Now, time travel I would hedge against. I think I agree with Dr. Shostak. But certainly the excitement about space travel, that's something that is very recent, and honestly technologically very possible.

Dr. ZURBUCHEN. The short answer is, I don't know, but the one thing I've learned in looking at science is never discount options.

Mr. ROHRABACHER. Now, again, I'm going to have a plebian approach to my questions, and that is, I watch the History channel, and I watch various things that are presented about things that we may have spotted on things like Mars where there are objects that appear to be walls. Are all of those objects, have you just written them off and they're not products of other civilizations?

Dr. SHOSTAK. I think it's safe to say they are not. I get emails and phone calls every day from people who claim they have good evidence of aliens visiting the solar system, and I wish it were true. I wish it were convincing. It would be job security for me, after all. But if you look at most of these claimed artifacts found on Mars by people who go through, for example, the Rover photos and so forth, I mean, they find, you know, little statuettes, they find critters like lizards, they find oceangoing creatures. They also—there's also a Nazi helmet. This may be news to you that the Wehrmacht actually went to Mars. All of this are examples of pareidolia, which is to say like looking up in the clouds, you can see almost anything you want.

Mr. ROHRABACHER. You rule out that any of these things, objects that we see are indicative of some lifeform?

Dr. SHOSTAK. There may be life on Mars but I don't think it's manifested in these images.

Mr. ROHRABACHER. What about you, sir?

Dr. KASTING. I agree with what Seth said, and the images are not convincing. I don't see as many as Seth does, but I'm interested in looking for Mars in the subsurface—looking for life in the subsurface.

Mr. ROHRABACHER. And?

Dr. BURGASSER. Yeah, I would also say I'm not convinced. I mean, we do—we have evolved as a species to have incredible pattern recognition powers and so we find patterns in lots of things. Outstanding claims require outstanding evidence.

Dr. ZURBUCHEN. Same here. Basically, I've been personally involved in more than one of these instances where something comes up and we attempt to deploy great scientists to go look at this. In some cases, it's just a camera effect. You know, you look at your own pictures and you see kind of weird things just because of how a camera works and sometimes it's like what he says, you know. It's the lion in the clouds, that type of thing.

Mr. ROHRABACHER. I know we're getting a great deal of understanding from your labor and your effort that you're putting in to this project, a great deal of better understanding of the nature of the universe, and we appreciate that and we appreciate your advice to us on how to be realistic about that as well. So thank you very much.

Chairman SMITH. Thank you, Mr. Rohrabacher.

The gentleman from California, Mr. McNerney, is recognized.

Mr. MCNERNEY. Well, again, I thank the Chairman for holding this hearing.

Dr. Shostak, about SETI, you mentioned that SETI's getting better at identifying targets and improving—and the equipment to be used is also improving. Could you elaborate on what's improving in terms of the detection and the equipment that's used to survey?

Dr. SHOSTAK. Yes. To some extent, there's an improvement simply in raw sensitivity so that you can find weaker signals, but that depends on having lots of antennas. That means putting up lots of physical structure. Aluminum hasn't gotten a whole lot cheaper in the last 20 years. So that's a very slow improvement there.

The big improvement is in the receiver technology where instead of looking at one star at a time, which is what we've done—when I say look at a star, of course you're assuming there may be planets around it that have somebody with a radio transmitter. Instead of looking at one at a time, you could in fact look at tens, hundreds, even thousands of stars at a time with enough computer processing capability, and of course, that capability is coming down the pike.

The other thing that we're beginning to deploy is what's called machine learning. This is where you use massive computing power to search for all kinds of patterns in the signals. Today we have sort of a dedicated machine that looks for one kind of pattern. It's sort of akin to having hearing where you can only hear one note. You're not going to really get a lot out of a symphony, but if you can, you know, use machine learning in this case to broaden the kind of thing you could recognize, then that will also speed up the search.

Mr. MCNERNEY. Let's—and I'm not sure who to ask this question, but what's the risk of contaminating other planets with—nearby planets, Mars and so on, with Earth biology?

Dr. ZURBUCHEN. For missions to places where we expect that could harbor life or any organism such as Mars or Europa, we use strict protocols referred to as planetary protection, and so basically what we do is go look at it in both ways. The first one is, we don't want to destroy an experiment so we actually take, you know, tremendous efforts to make sure that we don't bring a lot of our life there or organisms and so we don't destroy an experiment. The other thing, we also want to make sure if we found something and brought it back, and that's going to be important once we start bringing back samples from places like Mars and so forth, we want to make sure that if there was life in there that it's not kind of the equivalent of a really lethal virus. So, you know, the kind of mechanisms that we would use for such bacteria or viruses, we would use in this context so we have mechanisms that we use for every one of those missions, both classification and also how we actually build the missions and land them and so forth.

Mr. MCNERNEY. Dr. Kasting?

Dr. KASTING. Could I add a comment to that? I mentioned in my testimony that Cassini is going to crash into Saturn at the end of the summer. NASA's doing that intentionally for planetary protection reasons because they don't want—after they lose control of

Cassini, they don't want it to crash into one of Saturn's moons or the rings.

Mr. MCNERNEY. Another question is, I mean, with all the new information on exoplanets, is there a way to classify all this information or are we still sort of ad hoc trying to figure out how to put these things into some sort of order?

Dr. BURGASSER. So there are several groups in the exoplanet community that have gotten together to develop websites, databases that organizes information. I mentioned earlier in my testimony the University of Puerto Rico at Arecibo have built a laboratory, and they've developed criteria to assess the habitability of various planets. There are a number of great resources that compile the data on these 3,000-plus exoplanets, and again, those resources are publicly available, and so I often have my students do research projects to explore these catalogs and come up with their own measures of habitability and potential for life.

Mr. MCNERNEY. So is the—I mean, for someone that's not immersed in this issue, is there an ability to go to that resource and understand what's happening or is it still pretty foggy?

Dr. BURGASSER. No, and what I can do is, I can put in the written testimony some of these resources, but they actually have sort of demonstrations on how to use the data. They're extremely well designed, and they have gotten a lot of interest from the public.

Mr. MCNERNEY. Very good.

All right, Mr. Chairman. I'll yield back. Thank you.

Chairman SMITH. Thank you, Mr. McNerney.

Oh, without objection, the Ranking Member, Ms. Johnson, is recognized for an additional question or two.

Ms. JOHNSON. Thank you very much, Mr. Chairman. This really has been an exciting hearing, especially as we look toward the future, and I'm sorry Mr. Rohrabacher had to leave. Speaking of his 12-year-old son, it really is a thing that excites young men, young people when we can look to the future and start to explore the unknown, and in 30 years we might know a whole lot more than we know now, and my question really is to the panel here. What do we do as a Congress to make sure that in 30 years, we're on top of what's going on in the universe? How do we move forward? How well equipped will we make sure that our young minds are stimulated and interested in this area? I'm so grateful for those who came before us who made it possible for today, and thanks to all of you, but we have a challenge, Mr. Chairman.

Chairman SMITH. Thank you, Ms. Johnson.

Let me respond very quickly, and I think most members know that we are fortunate to have within our Committee's jurisdiction STEM education or many aspects of STEM education, and in fact, I believe the first two bills that President Trump signed last month were two STEM bills that were produced by this Committee, and I was over there for the bill signing. And we will continue to go in that direction.

The other thing I think that is good news for us is that most agencies had their budgets cut. NASA was one of the few agencies that did not incur any cuts, so we have an Administration, I think, and a Congress who is very interested in space and what's out there.

Let me thank our witnesses again today. You all have just been fascinating and informative, and we appreciate your taking the time to be here. Clearly, on the basis of the questions you were asked, there is interest across all members in what you're doing and the different things that you're doing as well. We heard things today we haven't heard before, and that's always enough to keep us going and have future hearings on the subject as well.

So thank you all for being here. We stand adjourned.

[Whereupon, at 11:36 a.m., the Committee was adjourned.]

Appendix I

ANSWERS TO POST-HEARING QUESTIONS

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Thomas Zurbuchen

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Advances in the Search for Life"

Dr. Thomas Zurbuchen, Associate Administrator, Science Mission Directorate, National Aeronautics and Space Administration (NASA)

Question submitted by Ranking Member Eddie Bernice Johnson, House Committee on Science, Space, and Technology

1. What steps has NASA taken in response to direction in the recently enacted NASA Transition Authorization Act of 2017 directing NASA to enter into an arrangement with the National Academies to develop a science strategy for astrobiology?

   Answer: NASA is currently engaged with the National Academies to finalize the study terms and establish an official contract. We anticipate standing up the committee and beginning the study in June 2017. Once underway, it is expected to take approximately one year to conduct the study, with additional time for peer review as deemed appropriate, and the final report to be submitted to Congress in the September 2018 timeframe.

2. In February, NASA released new details about its mission architecture for sending humans and robotic landers and rovers to the surface of Mars in the 2030s. While geologists and astrobiologists on the surface of Mars can make quick, intuitive decisions about which samples are most scientifically compelling, humans could introduce the potential for contaminating scientifically important environments. In your view, what are the risks and benefits of involving humans directly in the search for life, such as in carrying out investigations on the surface of Mars? What is NASA doing to characterize such risks so that steps toward mitigating them can be taken?

   Answer: Mars is the horizon goal for pioneering space but it is important to note that in this journey, the human and robotic explorers will play a complementary role. While robotic missions will serve as science and technology pathfinders for crewed missions to Mars, astronauts on the surface of the planet will be able to expand our knowledge and inform mission planning for further robotic exploration. Robotic explorers will also better inform future human explorers as to those areas that might be at risk of contamination from terrestrial life, and enable them take appropriate precautions. Astronauts will be able to collect a greater volume and diversity of rock and soil samples than would be possible using robots alone, but the potential to contaminate samples with biosignatures from Earth will be much higher. As was the case with the rock samples collected during the Apollo missions to the Moon, astronauts on the Martian surface will be able to make in situ judgments about samples to be retrieved, and will be able to record the context in which those samples were discovered, as well as the potential for Earth contamination to be introduced. Additionally, we expect astronauts on Mars to be able to analyze orders of magnitude more samples than get returned, and selecting samples with minimal Earth contamination will be important to assure the highest chance to detect signs of Martian life. Careful selection will also enhance other aspects of scientific quality in the samples that are selected to be returned to Earth. Continued robotic exploration of Mars will ensure that areas of the planet not as readily accessible to human crews do not go unexplored.

NASA recognizes there are inherent risks as well as benefits of involving humans directly in the search for life, and our planetary protection and mission planning teams are actively working together to evaluate mitigation strategies. We currently do not know whether the Martian environment contains biohazards that might cause problems for astronauts or affect the environment of the Earth. Under consideration is using sterilized teleoperated robots to explore those areas where contamination from human explorers is a concern for the environment of Mars, or where Earth contamination could interfere with the detection of possible Martian biohazards.

3. The Curiosity rover was only partially sterilized before going to Mars. How has partial sterilization affected the choice of areas Curiosity is able to explore in terms of addressing scientific objectives related to the search for life? What is the planetary protection category for the Mars 2020 rover? How does such a classification affect the regions of Mars the rover can study and the science it can do?

Answer: Curiosity's primary mission is to assess whether Mars ever was, or is still today, an environment able to support microbial life. Because it was not carrying instruments designed to search for evidence of extant Martian life, Curiosity was designated planetary protection Category IVa and subject to a biological contamination limit. The Curiosity rover complied with planetary protection requirements to carry a total of no more than 300,000 bacterial spores on any surface from which the spores could get into the Martian environment. The categorization of the mission and the resulting restrictions have not inhibited its ability to meet its primary science objectives.

If in the future, a site in Gale crater becomes identified as potentially a Special Region (where terrestrial microbial life might propagate), then Curiosity would be precluded from entering the site until further study determines the site is not at risk for contamination.

NASA has designated the Mars 2020 mission as Planetary Protection Category V: Restricted Earth Return, due to the presence of hardware intended to cache samples for future return to Earth, and appropriate requirements are being implemented accordingly. These include designing the sample collection hardware to meet stringent limits on Earth biological contamination introduced into samples collected for future return. As was the case for Curiosity, the primary constraint for the Mars 2020 mission is the restriction from landing in, entering, or creating, a Special Region on Mars. This should not affect the science results, as the Mars 2020 Science Definition Team report concluded that the primary mission objective of exploring an ancient environment does not require the mission to access Special Regions.

4. With the recent announcement from NASA of a potential second observation of plume activity on Europa, is there a push to alter the scientific goal of the NASA Europa Clipper mission to include life detection? How would such a decision be made? Is it possible to add life detection instruments to the spacecraft at this point in its development?

Answer: The ultimate aim of Europa Clipper is to determine if Europa is habitable, possessing all three of the ingredients necessary for life: liquid water, chemical ingredients for building biomolecules, and energy sources sufficient to support life. The nine instruments that NASA has selected for the mission will physically characterize the subsurface ocean, interrogate the surface for evidence of materials convected from the subsurface ocean, and chemically characterize that material. If the Europa Clipper encounters a plume, it would be able to make similar measurements to what Cassini was able to do at Enceladus. Analysis of a sample spewed directly from the subsurface ocean would prove more definitive information on the potential habitability of Europa.

Even though some of the nine instruments have limited capability to detect biomarkers, searching for life is easier if done by a lander on the surface or directly accessing the subsurface ocean. A lander payload would need to be designed to detect likely dilute evidence of life that has been lofted to the surface from the ocean deep below.

5. Last month, NASA announced that Cassini composition measurements revealed the presence of molecular hydrogen in the plume material spewing from the surface of Enceladus, thus providing an "independent line of evidence that hydrothermal activity is taking place in the Enceladus ocean." As you know, hydrothermal activity provides a necessary chemical energy source for life. What future verification and confirmation activities will logically flow from discoveries such as this and how can excitement be sustained until those activities can be undertaken?

Answer: Cassini has completed its data gathering at Enceladus, and the mission will reach its dramatic conclusion this September. But the analysis of Cassini data is far from complete. It will continue for years, fueling scientific advancements and refining our understanding of Enceladus. Coupling this work with research on hydrothermal systems on Earth is a proactive path forward, and the planetary science and Earth oceanographic communities are beginning to work together.

The information Europa Clipper will provide about Europa's ocean will be highly relevant to Enceladus and our search for life on Ocean Worlds. It is not unreasonable to surmise that the geophysics of Enceladus responsible for the observed hydrothermal activity is also operating on Europa. The scientific community is excited to confirm this activity on Europa and perhaps find evidence that some form of life is taking advantage of that hydrothermal energy source.

No further observations of Enceladus and its ocean will be possible until a new mission is launched. Such a mission is one of seven candidate destinations currently under competition in NASA's New Frontiers Program. Initial selections are expected this fall.

6. What is the status of the NASA Nexus for Exoplanet System Science (NExSS) initiative? What results have come from the initiative and what plans does NASA have for NExSS over the coming years?

Answer: NExSS is a NASA research coordination network dedicated to the study of planetary habitability. The goals of NExSS are to investigate the diversity of exoplanets and to learn how their history, geology, and climate interact to create the conditions for life. NExSS is overseen by representatives from NASA HQ, three co-leads, and a Steering Committee composed of the Principal Investigators (PIs) of 18 funded proposal teams selected to be the founding members of NExSS. These investigators are drawn from a diverse range of scientific backgrounds including astrophysics, Earth science, heliophysics, and planetary science and lead interdisciplinary teams ranging in size from 3 to over 50 members. Specifically, major areas of research focus include exoplanet detection, characterization, planetary formation processes, climatic evolution, paleoclimate and biogeochemistry, as well as microbiology, astrobiology, and the emergence of life. Moreover, NExSS supports two cross-team NASA Postdoctoral Program (NPP) Fellows, as well as a NASA Postdoctoral Management Program (NPMP) Fellow based at NASA Ames Research Center.

In the past year, Affiliate members have also been added to the NExSS network; these are individuals or groups whose research interests and vision are aligned with those of NExSS but who currently do not belong to any of the PI-led teams. Affiliates are invited to participate in NExSS's webinar series, attended conferences and workshops and contribute to science, data, and policy products in order to facilitate wider community engagement.

To date, NExSS has supported three 'Workshops Without Walls' (WwW) focused on the interior evolution of potentially habitable planets, the effect of 'space weather' on long-term planetary habitability, and the detection of remote biosignatures. Participants and speakers have attended in-person but also via weblink as the input and active engagement of remote participants has been emphasized to ensure representation from the wider local and international community. Products from these workshops have included white papers, new collaborations, and the identification of new questions, topics and research avenues. NExSS's most recent workshop resulted in a total of five review papers on the science and technology of remote searches for signs of life on exoplanets. These documents are currently in the stage of community comment and feedback, facilitated through NExSS's online infrastructure, in preparation for eventual submission to *Astrobiology* journal.

It can be difficult to quantify the effectiveness of research coordination networks as many of the successes of these initiatives cannot be easily measured. For example, NExSS's PIs note that several collaborative activities such as student exchanges, winter/summer schools, invited talks at department seminars and colloquia, as well as joint grant proposals have arisen from their interactions with the NExSS community.

Furthermore, organization is currently underway for NExSS's flagship meeting entitled *Habitable Worlds 2017: A Systems Science Workshop*, which will be held in November 2017 in Laramie, WY. This workshop will deviate slightly from the traditional format of science conferences in that emphasis on 'breakout' sessions on topics suggested by the participants are prioritized alongside talks and presentations. The workshop will seek to address broad questions pertaining to planetary habitability including what conditions are needed for habitability, how those conditions arise, and how we can best search for them.

NExSS began as an experiment in cross divisional cooperation and interdisciplinary research focused on habitability and the search for life beyond our solar system. The program has met our expectations and continues to build its impact and reach. As long as it enhances the science, feeds into our missions, and remains productive, NASA will continue to support the system science approach for studying exoplanets.

7. What is the status of NASA's plans for a future mission to return cached samples collected by the Mars 2020 rover so they can be studied by researchers on Earth? You mention in your statement that NASA is "exploring opportunities to partner with industry to leverage their future missions to advance decadal survey science objectives." Can you expand on that? When can we expect to get more details on when and how cached samples from Mars will be returned to Earth?

Answer: NASA has been studying concepts for returning samples collected by the Mars 2020 rover in the context of a larger Mars exploration architecture assessment, which was called for in the FY17 NASA Transition Authorization Act (PL 115-10). Consistent with the direction in the NASA Transition Authorization Act, this assessment would be conducted by the National Academies of Sciences, Engineering, and Medicine and would use the strategies and priorities described in the NRC Vision and Voyages for Planetary Science in the Decade 2013-2022 [the Planetary Science Decadal Survey] as a starting point. This assessment, which would consider opportunities for collaboration with commercial and international partners, would feed into the Administration's future Mars planning.

8. How do scientific and technological advances in astrobiology impact the way NASA sets its broader astrophysics science goals? In your view, are any changes to this process needed?

Answer: NASA recently created the Nexus for Exoplanet System Science (NExSS) research coordination network to leverage research investments in many fields to understand how planetary processes lead to potentially habitable exoplanets, as well as how the planet stars and neighbor planets interact to support life. This "system science" approach will help scientists better understand how biology interacts with the atmosphere, geology, oceans, and interior of a planet, and how these interactions are affected by the host star. This in turn help us better understand how to look for life on exoplanets. For instance, Earth-observing satellites has given us a wealth of information on the atmosphere of our home world, which we have utilized to 'groundtruth' the models and techniques that astrophysicists will use to analyze the atmospheres of other planets.

Scientific and technological advances in astrobiology will be incorporated into the upcoming 2020 Decadal Science Survey and will be used to set priorities for the next decade of astrophysics research. NASA believes that this process is working well and does not need to be changed.

Responses by Dr. Adam Burgasser

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Advances in the Search for Life"

Dr. Adam Burgasser, Professor of Physics, University of California, San Diego and UCSD Center for Astrophysics and Space Science; Fulbright Scholar

Question submitted by Ranking Member Eddie Bernice Johnson, House Committee on Science, Space, and Technology

1. How do scientific and technological advances in astrobiology impact the way NASA sets its broader astrophysics science goals? In your view, are there changes to this process needed?

   Answer: NASA is continually working with its scientists and researchers in the broader community to set and evaluate astrophysics science goals in the face of new research, new technological advances, and new opportunities. On a decadal timescale, the NASA Decadal Survey sets mission priorities of 10-20 year timescales based on current/likely technological capabilities; current scientific understanding in astrobiology, astrophysics and planetary science; and administrative priorities. This is a community-led effort, with researchers from various institutions, areas of expertise, and career status contributing either directly through committee service or in an advisory capacity through contributions of white papers. Planning for the 2020 Decadal Survey is already underway.

   Another example of community participation is the Exoplanet Exploration Program Analysis Group (ExoPAG), which is responsible for soliciting and coordinating community input into the development and execution of NASA's Exoplanet Exploration Program (ExEP). ExoPAG serves as a community-based, interdisciplinary forum for soliciting and coordinating community analysis and input in support of the Exoplanet Exploration Program objectives and of their implications for architecture planning and activity prioritization and for future exploration. It provides findings of analyses to the NASA Astrophysics Division Director. In-person ExoPAG community meetings occur twice a year, and additional meetings (in-person or virtual) occur when specific recommendations are solicited (e.g., in preparation for the Decadal Survey). These meetings are open to the public. The next ExoPAG meeting is scheduled June 18th in Mountainview, CA; see https://exoplanets.nasa.gov/exep/events/.

   In both cases, scientific and technological advances directly influence NASA's scientific priorities in the astrophysics realm through the scientists involved in these activities. Given the considerable degree of community engagement and immediate public dissemination of white papers and committee reports (e.g., https://exoplanets.nasa.gov/exep/resources/documents/exopagFoundingDocuments/), I personally feel this process is functioning well and no changes are immediately necessary.

Responses by Dr. James Kasting

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Advances in the Search for Life"

Dr. James Kasting, Chair, Planning Committee, Workshop on the Search for Life Across Space and Time, National Academies of Science, Engineering, and Medicine, Evan Pugh Professor of Geosciences, Pennsylvania State University

Question submitted by Ranking Member Eddie Bernice Johnson, House Committee on Science, Space, and Technology

1. What is the current understanding of how life got its start on Earth and how does and how should this understanding inform astrobiology research and mission development in NASA?

   Answer: Thank you for this question. It is a cogent one. I do no direct research on the origin of life myself, but I have been going to origin of life meetings for the past 35 years, and I have some understanding of the basic issues. My most fundamental observation is this: there is no scientific consensus about how life originated. Rather, it is one of the biggest unsolved problems in all of science. This does not mean, however, that we do not have hypotheses. In fact, there are scores of hypotheses dating back to the 1938 publication of Alexander Oparin's book: *The Origin of Life*. I will not attempt to summarize all the different ideas here. I will point out, though, that there are two main classes of ideas: 1) information first, sometimes called 'RNA first', and 2) metabolism first. Let me briefly describe how these work.

   1) The information first hypothesis is based on the view that RNA was the first molecule that had the ability to store genetic information. Today, genetic information is stored by DNA, not RNA. But (double-stranded) DNA is closely related to (single-stranded) RNA, and virtually all biologists agree that RNA preceded DNA as a genetic material. Because it is single-stranded, RNA can also catalyze biochemical reactions—a task that today is mostly carried out by (single-stranded) proteins. Many biologists now postulate the existence of an 'RNA World', in which RNA performed all of the tasks that today are carried out by RNA, DNA, and proteins. Some biologists think that the first living system was an RNA organism like those envisioned in the RNA World. The difficult part of this hypothesis is to figure out how RNA was formed in the first place. RNA is a rather complicated biomolecule, with four different nucleic acid bases attached to ribose backbones and then strung together in chains using tri-phosphate linkages. Critics of this hypothesis argue that this biochemistry is too complex to have been present in the first living system, and that something simpler, but still 'alive', must have preceded it.

   2) By contrast, the metabolism first hypothesis is based on the idea, universally accepted by biologists, that living organisms need to have a source of energy to power their metabolism. Humans, along with other animals and plants, power their metabolisms with respiration (reacting organic matter with oxygen to make carbon dioxide and water). Microorganisms are much more diverse in their metabolisms. Some use respiration, as we do, but others

others employ a variety of other chemical reactions, including fermentation, sulfate reduction, and methanogenesis, just to name a few. The metabolism first hypothesis postulates that life arose spontaneously as a consequence of large thermodynamic free energy gradients. Primitive organisms tapped these gradients to drive their metabolisms. A commonly cited example of where such a process may have occurred is an environment similar to midocean ridge hydrothermal vents, where today organisms use abundant carbon dioxide and hydrogen to make methane. (This is a particular version of the methanogenesis reaction, mentioned above.) This hypothesis has many attractive features, and indeed I favor it myself. Critics, though, argue that in the absence of RNA, there is no known genetic mechanism for passing information down from one organism to the next. Biologists have thought hard about this problem, but no one has demonstrated a convincing genetic mechanism to bridge the gap between the abiotic world and the RNA World.

This somewhat lengthy reply does not directly answer your question about how life originated, but it outlines some of the possibilities. Future NASA space missions may help us choose between these competing hypotheses. Continued study of Europa and Enceladus may shed additional light on the question of whether large free energy gradients exist in their subsurface oceans. In my written and oral testimony, I mentioned that new measurements of Enceladus' plume by the Cassini spacecraft indicated that large free energy gradients *may* exist for the methanogenesis reaction described above. This conclusion rests on a single measurement, though, and few astrobiologists would consider it to be definitive. More studies of plumes on Enceladus and Europa are needed, along with analyses of the material that wells up between the cracks on both of these icy moons.

A second way in which NASA space missions can address the origin of life issue is by telling us if it happened more than once. I am thinking here primarily of proposed large, direct-imaging space telescopes that can be used to find and spectroscopically characterize Earth-like planets around nearby stars. Such telescopes were also mentioned in my testimony. Some critics of *both* sets of hypotheses about the origin of life say that it is much too difficult a process to have happened by itself. Rather, it could only have happened at the hand of a divine Creator. It is difficult or impossible to prove such critics wrong. But by identifying signs of life on other Earth-like planets, we could at least answer the question of whether it happened more than once. To those of us with a scientific bent, this would suggest that the origin of life is a natural process that occurs whenever the conditions, e.g., large free energy gradients and the presence of liquid water, are favorable. Conversely, if we find lots of Earth-like planets, but no evidence for extraterrestrial life, that would lend credence to the views of those who argue that life on Earth is unique. Continued exploration of our solar system, combined with telescopic observation of nearby exoplanets, may help us answer this question.

2. How do scientific and technological advances in astrobiology impact the way NASA sets its broader astrophysics science goals? In your view, are any changes to this process needed?

Answer: Your question mentions astrophysics explicitly, as opposed to planetary science, so I will confine my answer to this area. As you probably know, Astronomy & Astrophysics and Planetary Science represent separate divisions within NASA's Space Science Directorate, and the scientific issues and technologies developed in these two areas are quite different.

The main tool used by astrobiologists within the Astronomy & Astrophysics Division at NASA is space telescopes. In my view, the scientific goals and technological needs of astrobiology fit right into the broader astrophysics science goals. One example is NASA's James Webb Space Telescope (JWST), which launches next year. JWST was designed primarily as a general purpose telescope for doing astrophysics. This gigantic (6.5-m) telescope will be used to study star formation, stellar disks, and many other phenomena that interest astronomers. At the same time, JWST will give us the best spectra yet of transiting exoplanets (planets that pass directly in front of their parent star). This is of great interest to planetary scientists and to astrobiologists, as it will provide information about exoplanet atmospheres, and it *may* provide indirect evidence for life.

A second way in which astrobiology science goals overlap with the interests of general astronomers is in the development of technology for future direct imaging telescopes. I keep coming back to this topic, because this is my own scientific passion. Such telescopes will use either a coronagraph or a starshade to block out the light from a star and look for reflected light from the planets orbiting around it. They will allow us to search for planets of all types around many of the nearby stars. They will observe many more planets than JWST, because the planets do not need to transit their parent star. A direct imaging telescope like HabEx (mentioned in my written testimony) would allow us to see all of the planets from Venus out to Saturn if we were looking at our own solar system from afar. So, it will at once allow us to learn the nature of planetary systems around most of the nearby stars. At the same time, it will also allow us to take spectra of the atmospheres of the most interesting exoplanets, those that lie within the liquid water habitable zone of their star. This is the information we need to look for signs of life. So, such a telescope would satisfy the desires of astrobiologists, as well as astronomers who are interested in the planets themselves.

So, to summarize, while the scientific goals of astrobiologists and astrophysicists are not necessarily the same, the tools they hope to develop are not that different. The NASA Astronomy & Astrophysics Division, under the leadership of Paul Hertz, is doing an excellent job of pursuing these new technologies, including those needed for direct imaging of exoplanets. To get such missions approved, astrobiologists will first need to get the support of the broader astronomical community, via the upcoming Astronomy & Astrophysics decadal survey. What they will need next is money. I hope that Congress recognizes the pioneering science being carried out presently by NASA astronomers/astrobiologists and that it provides them the resources to do even more such science in the future.

Responses by Dr. Seth Shostak

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Advances in the Search for Life"

Dr. Seth Shostak, Senior Astronomer, SETI Institute

Question submitted by Ranking Member Eddie Bernice Johnson, House Committee on Science, Space, and Technology

1. How do scientific and technological advances in astrobiology impact the way NASA sets its broader astrophysics science goals? In your view, are any changes to this process needed?

Answer: As in any scientific discipline, advances in one area affect others. Astrobiology is a relatively small tile in the larger mosaic of research, but its influence is to promote new instrumentation and studies in other areas, and to benefit from them. As obvious example, the development of very large optical telescopes is at least partially motivated by the seductive possibility of using them to "sniff" the atmospheres of exoplanets, one of the most promising ways to learn of planets with life. The construction of these telescopes is usually justified by the contributions they can make to cosmology – which is, of course, the province of some of the largest puzzles in science (dark matter, dark energy). But for the public, and for astrobiologists, it's the possibility of examining planets for signs of life that is appealing.

In general, the collaboration between NASA astrobiology and astrophysics functions well, at least from an outsider's perspective. I think there are two areas where change could be beneficial: (1) the length of competitive grants is too short. The researchers I know spend about one-fourth of their time writing grants, of which usually one in six are actually funded. That results in a very inefficient research effort, and one that, given the international competition in science today, should be ameliorated. Longer grants would mean a higher percentage of a scientist's time spent doing science. (2) While NASA has an extensive effort to probe the solar system for life, as well as a highly regarded astrobiology institute, the one aspect of this field in which it is no longer a participant is SETI. Despite my obvious bias in this matter, I think that this is more than regrettable. The public's interest in extraterrestrial life is greatest for intelligent life, and a modest NASA program could add a missing piece to the agency's tapestry of astrobiology research. We spend hundreds of millions of dollars and more to look for microbes on Mars and the moons of Jupiter and Saturn. For an additional one percent, NASA could also search for the type of life that would calibrate humanity's place in the cosmos, and bend the arc of our future.