PLANETARY FLAGSHIP MISSIONS: MARS ROVER 2020 AND EUROPA CLIPPER

HEARING

BEFORE THE

SUBCOMMITTEE ON SPACE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

ONE HUNDRED FIFTEENTH CONGRESS

FIRST SESSION

JULY 18, 2017

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PLANETARY FLAGSHIP MISSIONS: MARS ROVER 2020 AND EUROPA CLIPPER

TUESDAY, JULY 18, 2017

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

The Subcommittee met, pursuant to call, at 10:09 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Brian Babin [Chairman of the Subcommittee] 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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Planetary Flagship Missions: Mars Rover 2020 and Europa Clipper

Tuesday, July 18, 2017
10:00 a.m.
2318 Rayburn House Office Building

Witnesses

Dr. Jim Green, Planetary Science Division Director, Science Mission Directorate, NASA

Dr. Kenneth Farley, Mars Rover 2020 Project Scientist; Professor of Geochemistry, California Institute of Technology

Dr. Robert Pappalardo, Europa Clipper Project Scientist, Jet Propulsion Laboratory, California Institute of Technology

Dr. Linda T. Elkins-Tanton, Director and Foundation Professor, School of Earth and Space Exploration, Arizona State University; Principal Investigator, NASA Psyche Mission

Dr. William B. McKinnon, Co-Chair, National Academy of Sciences, Committee on Astrobiology and Planetary Science; Professor of Earth and Planetary Sciences, Washington University in St. Louis

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

Charter

TO:	Members, Committee on Science, Space, and Technology
FROM:	Majority Staff, Committee on Science, Space, and Technology
DATE:	July 18^{th}, 2017
SUBJECT:	Space Subcommittee Hearing: "Planetary Flagship Missions: Mars Rover 2020 and Europa Clipper"

On Tuesday, July 18^{th}, 2017 at 10:00 a.m. in Room 2318 of the Rayburn House Office Building, the Committee on Science, Space, and Technology, Subcommittee on Space, will hold a hearing titled, "Planetary Flagship Missions: Mars Rover 2020 and Europa Clipper."

Hearing Purpose

The purpose of the hearing is to examine current progress on Mars Rover 2020 and Europa Clipper, the science objectives of these flagship missions, and the prospects for a Europa lander. NASA's Planetary Science Division currently has two flagship missions in development, the Mars Rover 2020 and Europa Clipper flyby mission, and a Europa lander mission under study.

Witnesses

- **Dr. Jim Green**, Planetary Science Division Director, Science Mission Directorate, NASA
- **Dr. Kenneth Farley**, Mars Rover 2020 Project Scientist; Professor of Geochemistry, California Institute of Technology
- **Dr. Robert Pappalardo,** Europa Clipper Project Scientist, Jet Propulsion Laboratory, California Institute of Technology
- **Dr. Linda T. Elkins-Tanton**, Director and Foundation Professor, School of Earth and Space Exploration, Arizona State University; Principal Investigator, NASA Psyche Mission
- **Dr. William B. McKinnon**, Co-Chair, National Academy of Sciences, Committee on Astrobiology and Planetary Science; Professor of Earth and Planetary Sciences, Washington University in St. Louis

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 BABIN. The Subcommittee on Space will come to order.

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

And welcome to today's hearing titled "Planetary Flagship Missions: Mars Rover 2020 and Europa Clipper." I recognize myself for five minutes for an opening statement.

NASA's planetary science flagships are the crown jewels of our robotic exploration of the solar system. Viking, Voyager, Galileo, Cassini, Chandra, and Mars Science Laboratory are programs that have inspired generations of Americans. One need only visit a local elementary school to see the wonder in children's eyes as they learn about the great discoveries of these flagship missions. Mars Rover 2020 and the Europa Clipper will be no less amazing.

Upholding such a legacy is not easy. From its original recommendation by the National Academies, through formulation and development, and ultimately launch and mission operations, there is much work to be done to ensure mission success, that the taxpayers' money is being appropriately spent, and that the national interest is met.

Today's hearing serves an important oversight purpose. Our witnesses will provide important testimony on the Mars Rover 2020 and the Europa Clipper, from both a programmatic and science perspective. The hearing will also provide an opportunity for Committee members to learn about the science that these missions will conduct and how it will benefit our nation.

I have full faith that NASA and its hard working men and women will carry out its planetary science flagship missions successfully. That said, NASA is entering the most critical stage of the Mars Rover 2020 development and is undertaking the development of the Europa Clipper, and possibly a Europa Lander, at the same time.

For Mars Rover 2020, the NASA Inspector General reported concerns regarding an overly optimistic schedule for Mars Rover 2020 based largely on technology development challenges. I look forward to hearing from Dr. Green about these issues and how NASA is addressing them.

A fundamental oversight question that needs to be addressed is how developing and operating these flagship missions at the same time, including a possible lander, will affect the Planetary Science Division and broader Science Mission Directorate portfolio. NASA must remain vigilant to protect against potential cost growth or mission creep that could impact other activities.

The Consolidated Appropriations Act of 2017 funded and requires a Europa lander mission to complement the Clipper. The Act directed NASA to launch the Clipper in 2022 and a lander in 2024.

In the fiscal year 2018 President's budget, his request does not include funding for a Europa lander. NASA says that because the Planetary Science division already supports two other large strategic missions, Mars Rover 2020 and Europa Clipper, it cannot accommodate a Europa lander without significant impacts to other programs, and while a Europa lander is not included in the fiscal year 2018 budget request from the Administration, it has become an established concept for the future. NASA's Europa Lander Science Definition Team conducted a study on the topic in 2016 to evaluate landing on Europa and assess the science value and engineering design of a future lander mission. More recently, NASA released a community announcement to ask scientists what instruments would befit a Europa lander and NASA continues to work on lander design concepts.

I strongly support NASA and its efforts with the Mars Rover 2020 and Europa Clipper. I also believe there is great value in exploring the possibility of a Europa lander. However, it is critical that as Congress and NASA moves forward, we do our due diligence to assure not only flagship mission success, but also the success of the entire Planetary Science portfolio. I'd like to highlight the importance of sufficient research and analysis funding so that scientists can actually study the data derived from these missions.

I want to thank the witnesses for being here today and I look forward to your testimonies.

[The prepared statement of Mr. Babin follows:]

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

For Immediate Release
July 18, 2017

Media Contact: Kristina Baum
(202) 225-6371

Statement of Space Subcommittee Chairman Brian Babin (R-Texas)
Planetary Flagship Missions: Mars Rover 2020 and Europa Clipper

Chairman Babin: NASA's planetary science flagships are the crown jewels of our robotic exploration of the solar system. *Viking, Voyager, Galileo, Cassini, Chandra,* and *Mars Science Laboratory* are programs that have inspired generations of Americans. One need only visit a local elementary school to see the wonder in our children's eyes as they learn about the great discoveries of these flagship missions. *Mars Rover 2020* and the *Europa Clipper* will be no less amazing.

Upholding such a legacy is not easy. From its original recommendation by the National Academies, through formulation and development, and ultimately launch and mission operations, there is much work to be done to ensure mission success, that the taxpayers' money is appropriately spent, and that the national interest is met.

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For *Mars Rover 2020*, the NASA Inspector General reported concerns regarding an overly optimistic schedule for *Mars Rover 2020* based largely on technology development challenges. I look forward to hearing from Dr. Green about these issues and how NASA is addressing them.

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I thank the witnesses for being here today and look forward to their testimonies.

###

Chairman BABIN. And now I recognize the Ranking Member, the gentleman from California, for an opening statement. Mr. Bera.

Mr. BERA. Thank you, Mr. Chairman. And I had to look back there. I see my old friend, our former colleague, Congressman Matt Salmon, in the audience. We miss you, Matt. Thanks for being here.

Chairman BABIN. I just saw him too.

Mr. BERA. You know, thank you for holding this hearing, "Planetary Flagship Missions: Mars Rover 2020 and Europa Clipper." I think for both of us, we've talked about this, and for many of us of a generation that grew up in the space race, just the imagination, thinking about, you know, whether it was going to the moon or beyond, the Apollo missions to Skylab to Apollo-Soyuz to the space shuttle programs captured our imagination, and to a new generation of our kids and grandkids, they continue to capture our imagination of going beyond.

We live in a time where we've sent spacecraft to explore the moon, all eight planets, Pluto, several asteroids and comets. And just last week, the NASA Juno spacecraft provided us an amazing view of Jupiter's mysterious Great Red Spot. So, you know, these missions are incredibly important because it allows us to know that we're part of something bigger, and now we've got Voyager One that is traveling through interstellar space. The reach of our scientific exploration is truly inspiring.

And to maximize the scientific return on investment for planetary exploration, NASA develops both large and small missions to visit a range of destinations throughout our solar system. We're here to talk about large flagship missions like Mars 2020 and Europa Clipper missions because they play an important role in using complex instruments to help us understand the challenge of exploring hard-to-reach locations but we spend less time talking about the smaller missions, like the Psyche mission that's represented on our panel. These are launched more frequently in response to new discoveries. These missions also provide opportunities for students to engage in mission design, development, and operation. So the mixture of both the large planetary missions but also the small is an intentional mix and it provides significant value and has through the history of NASA's planetary science program.

We also know that NASA's planetary missions have greatly advanced our understanding of the solar system and its potential to harbor life beyond Earth. Now, imagine if we were to identify life beyond Earth. That would be disruptive for all of humanity in a way of answering that seminal question, are we alone? And, you know, life may not be in the form of human life. It may be microbiotic life, et cetera, but even that discovery would be dramatic and change how we viewed ourselves in the context of our universe.

So I look forward to learning more about the role of large and small planetary missions and the importance of supporting this balanced mission size and, you know, I want to acknowledge the panel here. I also want to acknowledge the long-term commitments that we make as a body to fund this discovery, and it's incredibly important to us.

So with that, I'll 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
Subcommittee on Space
"In-Space Propulsion: Strategic Choices and Options"
June 29, 2017

Good morning. And welcome to our distinguished panel.

Thank you Mr. Chairman for calling this important hearing to look at ongoing developments in advanced in-space propulsion technologies.

Chemical propulsion remains a critical part of today's human exploration program. Indeed, the two rocket boosters on NASA's Space Launch System use a solid chemical propellant and SLS's RS-25 core stage rockets utilize liquid chemical propellant. However, relying solely on chemical propulsion for deep space travel would result in spacecraft having to carry large amounts of propellant, possibly requiring multiple launches even before a mission can be initiated. That is why many experts believe that NASA will need advanced propulsion systems to power the agency's future robotic and manned spacecraft.

NASA is currently using non-chemical in-space propulsion in the form of electric propulsion. Electric propulsion is a continuous, low thrust process and has been used by a few NASA robotic spacecraft, such as the Dawn probe which has investigated the asteroid Vesta and is now orbiting Ceres.

Department of Defense (DoD) space vehicles and commercial satellites also make use of solar electric power, but primarily for orbit raising and repositioning. For example, each Advanced Extremely High Frequency (AEHF) Space Vehicle, which provides critical global communications to our warfighters, uses solar electric propulsion subsystems.

Another type of in-space propulsion—enabled through the use of nuclear reactors—was studied to a limited extent in the 1960s. However, engineers found that the amount of shielding needed to protect crew from the dangerous effects of prolonged exposure to radiation generated by the nuclear reactor as well as other technical difficulties were challenges that were hard to overcome at that time.

With plans now focusing on extended human travel into space, research into all forms of advanced propulsion technologies, including nuclear fission, is likely to intensify in the years ahead. It's critical that we find ways to reduce the time crew is exposed to galactic cosmic rays and other dangerous deep-space radiation. Significantly reducing mission duration times can only be achieved through advanced in-space propulsion.

As NASA continues developing our plans on how to send humans to Mars and returning them safely to Earth, now is a good time to examine the present and future options for in-space propulsion. Mr. Chairman, I am looking forward to hearing from our witnesses about different propulsion technologies and the unique characteristics that make them best suited to particular missions in space.

Thank you and I yield back.

Chairman BABIN. Thank you, Mr. Bera.

I now recognize the Ranking Member of the full Committee for a statement. Ms. Johnson.

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

Before I get into my formal statement, I just want to take a moment to say that this Friday marks 48 years of Apollo 11 moon landing, and as we look forward to inspiring our younger generation, whom I know many are sitting right out there, for the exciting future missions to Mars, Europa and asteroids, just remember that just 48 years ago this Friday, we had a previous generation of young people. America has an impressive legacy of accomplishment in both robotic and human space exploration, and I hope that we can continue to build on it. I hope that your minds will be just as inspired for our future as we have seen for our past. Now for my formal statement.

Let me welcome all of our witnesses. I look forward to your testimony.

Mr. Chairman, I thank you for holding this hearing on planetary flagship missions. Through our investigations in NASA's planetary science program, NASA has been able to explore every planet in the solar system, as well as Pluto; continuously operate missions to Mars for the past two decades; and discover an expanding realm of potentially habitable bodies both within and beyond the solar system. With each discovery, NASA is advancing knowledge, pushing technological boundaries, and inspiring future generations to pursue science and technology education and careers. That is why I have often referred to NASA's science program as one of America's crown jewels.

And we will hear this morning even more exciting planetary science missions lie ahead. As I speak, NASA is developing two planetary flagship missions. The Mars 2020 Rover will assess the habitability of Mars and look for signs of past life. In addition, the Europa Clipper mission will investigate the ice shell of Jupiter's moon Europa and its underlying ocean, helping scientists to assess whether it can support life. These, like previous flagships, are very challenging missions. Mars 2020 will drill, collect, and cache samples of Martian rocks and soils, and Europa Clipper must withstand the intense radiation environment of Jupiter. Fortunately, NASA has decades of experience with flagship missions to draw on.

With that in mind, I hope our witnesses can discuss the lessons learned from previous flagships and how we are using that knowledge in developing the Mars 2020 and Europa Clipper missions.

Mr. Chairman, a discussion of flagship missions would be incomplete without mentioning the importance of balance in mission sizes, a critical element of a robust portfolio for both the National Academies and NASA Authorization Acts have repeatedly emphasized.

To that end, I am pleased that this morning's discussion will also include smaller, Discovery-class missions, and their role in maintaining a productive and balanced planetary science program. Looking ahead, opportunities for new and exciting planetary science missions abound. Maintaining balance will take discipline among NASA, the scientific community, and Congress.

Before I close, I want to take a moment to thank the talented, dedicated and committed workforce of NASA and its university, industry, and international partners. Our Nation's inspiring achievements in planetary science would not be possible without all of you.

I thank you, Mr. Chairman, and yield back.

[The prepared statement of Ms. Johnson follows:]

<u>OPENING STATEMENT</u>
Ranking Member Eddie Bernice Johnson (D-TX)

Committee on Science, Space, and Technology
Subcommittee on Space
"In-Space Propulsion: Strategic Choices and Options"
June 29, 2017

Good morning. And welcome to our witnesses. I look forward to your testimony.

Mr. Chairman, I appreciate the opportunity to discuss in-space propulsion with a wide range of government, academic, and industry experts. In-space propulsion will be a critical enabler of our future missions, especially those involving human exploration beyond Earth orbit. And it is important that the Subcommittee assess the state of research and development related to in-space propulsion technologies, which NASA, the National Academies, and the NASA Advisory Council all consider to be a priority. Not only is this technology important for NASA and our space program, but it would also have benefits for the commercial sector, which already uses electric propulsion for maintaining commercial satellite positioning.

Mr. Chairman, I am looking forward to hearing from our witnesses about the range and types of in-space propulsion technologies being studied and the progress of the research and development into each. When we consider progress, we also need to understand whether sufficient resources are being invested to make sure the technologies will be ready when NASA needs them. It is important to note that the budget for NASA's Space Technology Mission Directorate, which includes work on in-space propulsion, has been relatively flat. Can we achieve the milestones for the needed technology development on a flat budget?

Mr. Chairman, our investments in research and development of enabling technologies such as in-space propulsion are our "seed corn" for achieving our goals for space exploration. It is our job to ensure that what we make the needed investments.

Thank you, and I yield back.

Chairman BABIN. Thank you, Ms. Johnson.

I now recognize our Chairman of our full Committee, Mr. Smith from Texas.

Chairman SMITH. Thank you, Mr. Chairman.

The exploration of our solar system captures Americans' interests, inspires us to pursue extraordinary goals, and keeps us on the forefront of scientific achievement.

Planetary missions teach us about how our solar system works and provide clues about how it was formed. They discover the locations of minerals and potential water sources on asteroids, comets, moons, and planets that could be used on future human missions or, in the case of minerals, extracted for use here on Earth.

Planetary science also helps address a fundamental question of science: Is there life elsewhere in the universe? Within our own solar system, scientists have found strong evidence that other planetary systems could in fact host life.

Europa, one of Jupiter's many moons, may have the necessary ingredients for life: water and energy. Its ocean lies beneath an icy surface and may be two times the volume of all Earth's oceans. Tidal forces drive active geological processes within Europa's ocean interior and provide energy. Scientists see similar activity in hydrothermal vents on Earth's ocean floor.

The Europa Clipper mission, a flagship mission recommended by the National Academy of Sciences, will be an important mission to address the scientific question of whether there is life elsewhere in the universe. It will advance our understanding of planetary science as it explores the characteristics of Europa's oceans, ice surface, and other geological activity.

Congress directed NASA to work on a Europa lander to complement the Europa Clipper. NASA's Europa Lander Science Definition Team conducted a study on the topic in 2016. The study found that the mission could analyze the biological potential of Europa's ocean by directly examining both Europa's surface and sub-surface. This is a very exciting concept that warrants NASA's continued efforts.

Closer to Earth, Mars Rover 2020 will also study the habitability of Mars. It builds upon the discoveries from the Mars Curiosity rover and the two Mars Exploration rovers, Spirit and Opportunity. The mission not only seeks signs of habitable conditions in Mars' past, but also searches for signs of past microbial life itself. It will also test new technology that could benefit future robotic and human exploration of Mars. One of its instruments, MOXIE, will test a method for producing oxygen from the Martian atmosphere. Oxygen production on Mars will be critical for future human missions.

I appreciate NASA's planetary science exploration efforts and the Trump Administration's support of American leadership in space. Other than national security agencies, NASA received the most favorable budget request from the Trump Administration. As a result, we can look forward to NASA undertaking a bold and ambitious agenda.

I thank our witnesses and look forward to their testimony, and I'll yield back, Mr. Chairman.

[The prepared statement of Mr. Smith follows:]

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

For Immediate Release
July 18, 2017

Media Contact: Kristina Baum
(202) 225-6371

Statement of Chairman Lamar Smith (R-Texas)
Planetary Flagship Missions: Mars Rover 2020 and Europa Clipper

Chairman Smith: Thank you, Chairman Babin.

The exploration of our solar system captures Americans' interests, inspires us to pursue extraordinary goals, and keeps us on the forefront of scientific achievement.

Planetary missions teach us about how our solar system works and provide clues about how it was formed. They discover the locations of minerals and potential water sources on asteroids, comets, moons, and planets that could be used on future human missions or, in the case of minerals, extracted for use here on Earth.

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I thank our witnesses and look forward to their testimony.

###

Chairman BABIN. Thank you, Mr. Chairman.

Now let me introduce our witnesses. We have a distinguished panel this morning.

Our first witness today is Dr. Jim Green, the Director of the Planetary Science Division of the Science Mission Directorate at NASA. Welcome. Dr. Green has served as the Chief of the Space Science Data Operations Office at Goddard Space Center as well as the Co-Investigator and Deputy Project Scientist on the IMAGE mission. He received his Ph.D. in space physics from the University of Iowa. Welcome.

Our second witness today is Dr. Ken Farley, the Mars Rover 2020 Project Scientist. He is also a Professor of Geochemistry at the California Institute of Technology. He received his bachelor of science in chemistry from Yale and a doctorate in earth science from the Scripps Institution of Oceanography from the University of California in San Diego. Welcome.

Our third witness today is Dr. Robert Pappalardo, the Europa Clipper Project Scientist at JPL at the California Institute of Technology. Dr. Pappalardo received his bachelor of arts in geological sciences from Cornell University as well as Ph.D. in geology from Arizona State University. Maybe that's why we see Representative Matt Salmon back there.

Dr. Linda T. Elkins-Tanton, our fourth witness today, Director and Foundation Professor at the School of Earth and Space Exploration at Arizona State University. She is also the Principal Investigator for the NASA Psyche Mission. She received her bachelor's of science and her master's of science as well as her Ph.D. from MIT.

Our fifth witness today is Dr. William B. McKinnon. He is Co-Chair of National Academy of Sciences' Committee on Astrobiology and Planetary Science. He is also a Professor of Earth and Planetary Sciences at Washington University in St. Louis. He received his bachelor of science degree in Earth and planetary sciences from MIT and his Ph.D. in planetary science and geophysics from Cal Tech.

I would like to now recognize Dr. Green for five minutes to present his testimony.

TESTIMONY OF DR. JIM GREEN, PLANETARY SCIENCE DIVISION DIRECTOR, SCIENCE MISSION DIRECTORATE, NASA

Dr. GREEN. Chairman Babin and the Members of the Committee, thank you so very much for giving us the opportunity to come and talk about certainly my favorite subject: planetary science. In my opening statement, I'd like to explain how missions like Mars 2020 and the Europa Clipper fit into an overall planetary exploration portfolio.

[Chart]

In my first chart, as you see, this is an overview of the current planetary missions. They're in a variety of formulation, implementation and currently operating missions that we have.

This is a tremendously exciting time in planetary science. All our operating missions are making revolutionary discoveries and all are rewriting the textbooks.

For instance, just two years ago, we had a fabulous fly-by of the New Horizon spacecraft through the Pluto system. With that mission, the United States becomes the first and only Nation to reach every major body in the solar system from Mercury to Pluto. Dr. Bill McKinnon on the panel is a New Horizons Co-Investigator.

Today, NASA has numerous missions exploring and operating through the solar system such as the lunar reconnaissance orbiter, which is bringing us back to the moon and making exciting discoveries.

The indomitable Mars Curiosity and Opportunity rovers along with our orbiters at Mars continue to make almost daily new discoveries about the red planet. For example, from our Maven mission, it has revealed that solar wind interactions with the upper atmosphere of Mars over time has literally stripped away most of that atmosphere, transforming Mars from what we believe was once a planet that could have supported life in its distant past to now a frigid, arid world.

Adding to our Mars missions, Insight lander will be launched in May 2018 and land in November 2018. Insight is designed to study the interior of Mars along with understanding its present-day level of global seismic activity.

In 2020, a new Mars rover will be launched carrying seven state-of-the-art instruments to conduct advanced geological research and search for signs of ancient Mars life. For the very first time, we will create high-grade rock core samples for potential return to Earth for further analysis. I look forward to Dr. Farley's testimony, which will provide additional information on that mission.

Between Mars and Jupiter is a major asteroid belt where NASA's Dawn mission is currently studying the dwarf planet Ceres and finding evidence of past cryovolcanism.

This year, NASA selected two discovery missions, Lucy and Psyche, which will respectively visit six Jupiter mysterious Trojan asteroids and study a unique metal asteroid that may actually be an exposed planetary core called Psyche. Dr. Linda Elkins-Tanton is here today to tell much more about the Psyche mission.

NASA's robotic rendezvous and sample return mission that visits the Bennu asteroid is called OSIRIS–Rex. It will get a gravity assist by Earth in September and it will reach that potentially hazardous asteroid in August of next year. Examinations of objects like Bennu will allow our scientists to investigate how planets formed and how materials like water and organics actually were delivered in early impacts in addition to looking at the effects of potential planetary defense.

In our outer solar system, Jupiter's mission Juno, which got into polar orbit our very first time in polar orbit at Jupiter last July. Since then Juno has been observing the cloud tops and into the interior of the planet, finding in the northern and southern polar regions that that planet is maintaining huge nearly Earth-size cyclones.

After 13 years of orbiting Saturn, our Cassini spacecraft is making a daring dive between the planet's atmosphere and the first ring, and it will lead to plunging that spacecraft into Saturn on September 15 as it runs out of fuel. Cassini has given us a powerful insight into the planet's internal structure, atmosphere and rings in addition to unbelievable views of Titan and Enceladus.

And if I may go on and summarize, finally, NASA recognizes there is still much to learn. With your support, we will continue to tackle solar system exploration goals identified as top priorities by the scientific community and delineated in the National Academies' Planetary Decadal.

Again, thank you so much for the opportunity to testify today and I look forward to responding to your questions.

[The prepared statement of Dr. Green follows:]

Statement of
Dr. James L. Green
Director, Planetary Science Division
Science Mission Directorate
National Aeronautics and Space Administration

before the

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

Chairman Smith and Members of the Committee, thank you for the opportunity to appear today to discuss NASA's Planetary Science program. In my opening statement, I would like to explain how the Mars 2020 and Europa Clipper mission fit into our overall planetary exploration portfolio.

NASA is at the leading edge of a journey of scientific discovery that promises to reveal new knowledge of our solar system's content, origin, evolution and the potential for life elsewhere. NASA Planetary Science is engaged in one of the oldest of scientific pursuits: the observation and discovery of our solar system's planetary objects. NASA advances the scientific understanding of the solar system in extraordinary ways, while pushing the limits of spacecraft and robotic engineering design and operations.

In the past couple of years, with the flyby of the New Horizons spacecraft through the Pluto system, humankind had completed its initial survey of our Solar System neighborhood. The United States remains the first and only nation to reach every major body from Mercury to Pluto with a space probe. Solar System exploration has always been and continues to be a grand human enterprise that seeks to discover the nature and origin of the celestial bodies among which we live and to explore whether life exists beyond Earth.

Today, NASA has numerous missions exploring and operating throughout the solar system. After the spectacular flyby of Pluto and its moons, New Horizons will encounter a small Kuiper Belt object (KBO), a building block of Pluto-sized KBOs on January 1, 2019. Missions such as the Lunar Reconnaissance Orbiter brought us back to the Moon and enabled new discoveries that are rewriting textbooks.

The indomitable Curiosity and Opportunity rovers supported by the Odyssey, Mars Reconnaissance Orbiter, and MAVEN (Mars Atmosphere and Volatile EvolutioN) orbiters at Mars are informing us about one of our closest neighbors. For example, this past March, results from NASA's MAVEN mission revealed that the solar wind is responsible, over billions of years, for stripping away most of the Martian atmosphere, transforming Mars from a planet that could have supported life in its distant past into the frigid, desert world that we see today. This discovery is a significant step towards unraveling the mystery of Mars' past environments and, in a broader context, informs us about the processes that can change a planet's habitability over time.

Adding to our missions at Mars, the InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) lander will be launched in May 2018 and land on the surface in November. InSight is designed as a seismic and heat flow subsurface probe that will study the interior structure of Mars along with understanding its present-day level of global activity. And just two years later, the Mars 2020 rover will launch, carrying seven instruments to conduct geological assessments on the Martian surface, determine the potential habitability of the environment, directly search for signs of ancient Martian life, and for the first time, collect high-grade rock core samples for potential future return to Earth. I look forward to Dr. Farley's testimony which will provide additional details about the Mars 2020 mission.

Between Mars and Jupiter is the main asteroid belt; where NASA's Dawn mission is currently studying the dwarf planet, Ceres – the largest object in the main asteroid belt. A few short months ago, scientists using Dawn's instruments found evidence of organic materials in and around Ceres' northern hemisphere crater called Ernutet. This discovery is the first clear detection of such molecules from orbit on a main belt body and interesting to scientists because organic molecules are necessary, though not sufficient, components of life on Earth.

However, Ceres is not the only small body NASA is investigating. This past January, NASA selected two new Discovery missions, called Lucy and Psyche, which will visit asteroids we have never seen up close before to enable groundbreaking science. Lucy will visit six of Jupiter's mysterious Trojan asteroids, while Psyche will study a unique, metal asteroid (16 Psyche) thought to be an exposed planetary iron-nickel core.

Moreover, NASA's current robotic asteroid rendezvous and sample return mission, dubbed OSIRIS-REx (for Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer) recently conducted a search of elusive objects known as Earth-Trojan asteroids during its current journey to the asteroid Bennu. Although no Earth-Trojans were discovered, the spacecraft's camera operated flawlessly and demonstrated that it could image objects significantly dimmer than originally expected. In September, OSIRIS-REx will flyby the Earth, getting the gravity assist it needs to arrive at its destination in August 2018. The first U.S. mission of its kind, OSIRIS-REx will approach the near-Earth Asteroid Bennu, map the asteroid, and collect a sample of as much as 1 kilogram for return to Earth in 2023. Bennu is believed to contain water and organic compounds such as amino acids. Examination of objects like Bennu will allow scientists to investigate how planets formed and how materials, like water, could have been brought to early Earth from later impacts.

NASA's Planetary Defense Coordination Office (PDCO) ensures the early detection of potentially hazardous objects and leads the research into impact mitigation and deflection strategies. PDCO's Near-Earth Object (NEO) Observations Program supports surveys that contribute to a sustained and productive campaign to find and track NEOs, collecting data of sufficient precision to allow accurate predictions of the future trajectories of discovered objects. To date, NASA-funded survey projects have catalogued more than 16,000 objects, at a current rate of about 1,500 per year – none of which pose a significant risk of impact with Earth over the next 100 years.

In our outer solar system, NASA's Juno spacecraft achieved a first-ever polar orbit at Jupiter last July and has shown us Jupiter in exquisite detail never seen before. Indeed, Juno has uncovered that Jupiter's magnetic fields are more complicated than originally thought. Juno has revealed that the belts and zones that give the planet's cloud tops their distinctive look extend deep into its interior, that the core of the planet is larger than expected, and that both northern and southern polar regions maintain numerous Earth-sized cyclones.

After 13 years orbiting Saturn, our Cassini spacecraft has completed 13 of a series of 22 daring dives through the 1,500-mile-wide gap between the planet and its rings as part of the mission's Grand Finale. Between April and September of this year, the mission team hopes to gain powerful insights into the planet's internal structure and the origins of the rings, obtain the first-ever sampling of Saturn's atmosphere and particles coming from the main rings, and capture the closest-ever views of Saturn's clouds and inner rings. When Cassini makes its final plunge into Saturn's atmosphere on September 15th, it will send data from several instruments - most notably, data on the atmosphere's composition - until its signal is lost.

And while Cassini may be ending this year, another outer planet mission is just getting started. NASA is working on a mission called Europa Clipper that will send a highly capable, radiation-tolerant spacecraft into a long, looping orbit around Jupiter to perform repeated close flybys of Europa, one of the most fascinating of Jupiter's moons. Europa is believed to harbor a salty ocean underneath a thick crust of ice. The goal of this mission is to conduct a detailed reconnaissance of Europa and to answer the big question, "Is Europa habitable?" Testimony from Dr. Pappalardo, of NASA's Jet Propulsion Laboratory, will provide exciting details about this future mission.

With such a vast array of ground-breaking missions, it is no surprise that NASA has always strived to develop creative and innovative ways to explore our solar system. Moving forward with that same perspective, NASA's Science Mission Directorate is incorporating a new initiative this year to use small, less expensive satellites (CubeSats or SmallSats) to advance selected high-priority science objectives in a cost-effective manner. This initiative will implement recommendations from the National Academy of Sciences, which concluded that, due to recent technological progress, these small satellites are suitable to address such science goals. The initiative will also provide partnership opportunities for commercial partners and our international counterparts to further leverage and align with investments made within NASA.

NASA's Planetary Science Division, in particular, has selected nineteen mission concept studies to define planetary science investigations that can be accomplished using small secondary payloads. The science targets under study span the solar system, including Mars, the outer planets, Venus, small bodies, and the Moon. The types of science proposed using CubeSats include determining the processes that control the climate on Mars, characterizing the composition of Venus' atmosphere, and exploring the interior structure of near-Earth asteroids. Other concepts include landers on the Moon to determine the age and structure of irregular surface features, and small spacecraft to characterize the solar wind upstream of Jupiter.

Finally, NASA recognizes there is still much to learn. On a grand scale, the solar system is a natural laboratory, within which we seek to unravel the mysteries of the universe and our place within it. With your support, we will continue to tackle solar system exploration goals identified as top priorities by the planetary science community and advance along the path of discovery and innovation for future generations to come.

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

Dr. Jim Green, Planetary Science Division Director, NASA HQ

Dr. Green received his Ph.D. in Space Physics from the University of Iowa in 1979 and began working in the Magnetospheric Physics Branch at NASA's Marshall Space Flight Center (MSFC) in 1980. At Marshall, Dr. Green developed and managed the Space Physics Analysis Network that provided scientists all over the world with rapid access to data, to other scientists, and to specific NASA computer and information resources.

From 1985 to 1992 he was the head of the National Space Science Data Center (NSSDC) at Goddard Space Flight Center (GSFC). The NSSDC is NASA's largest space science data archive. In 1992, he became the Chief of the Space Science Data Operations Office until 2005, when he became the Chief of the Science Proposal Support Office. While at GSFC, Dr. Green was a co-investigator and the Deputy Project Scientist on the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) mission. He has written over 100 scientific articles in refereed journals involving various aspects of the Earth's and Jupiter's magnetospheres and over 50 technical articles on various aspects of data systems and networks.

In August 2006, Dr. Green became the Director of the Planetary Science Division at NASA Headquarters. Over his career, Dr. Green has received numerous awards. In 1988, he received the Arthur S. Flemming award given for outstanding individual performance in the federal government and was awarded Japan's Kotani Prize in 1996 in recognition of his international science data management activities.

Chairman BABIN. Thank you, Dr. Green.

I now recognize Dr. Farley for five minutes to present your testimony.

TESTIMONY OF DR. KENNETH FARLEY, MARS ROVER 2020 PROJECT SCIENTIST; PROFESSOR OF GEOCHEMISTRY, CALIFORNIA INSTITUTE OF TECHNOLOGY

Dr. FARLEY. Thank you for the opportunity to testify today on the Mars 2020 mission.

Mars 2020 will seek evidence of past life in a fossil Earth-like environment that existed in the first billion years after the dawn of the solar system. This flagship mission will engage many hundreds of scientists and the American public in a very challenging journey through one of the most intriguing landscapes in the solar system and some of the most profound scientific questions of our time.

Today Mars is too cold, too dry, and too exposed to harmful radiation to plausibly nurture life on its surface. However, more than two decades of sustained and strategic NASA-led exploration have shown that the red planet was once very different. Imagery from the Mars Odyssey and Mars Reconnaissance Orbiters reveals that prior to about 3.6 billion years ago, Mars had rivers, lakes, and possibly a vast northern ocean. Sophisticated analyses made on the planet's surface, most notably by the Spirit and Curiosity rovers, have richly documented ancient environments with all conditions believed necessary to sustain life. In that same early time period, conditions here on Earth were broadly similar, and life had already originated, evolved, and spread across the surface. However, unlike Earth, with its active erosion and plate tectonics, the geologic record of ancient Mars is exquisitely preserved for study, allowing us to seek answers to grand questions including how early climate and habitability evolve on rocky planets, the nature of prebiotic environments that might ultimately spawn life, and whether life is unique to Earth. Seeking the signs of life in an ancient habitable environment is the central goal of the Mars 2020 mission.

Thanks to a wealth of images from the Mars Reconnaissance Orbiter, the science community has narrowed the possible Mars 2020 landing sites down to three very different settings that on Earth are both habitable and inhabited: an ancient river and lake system, a fossil hot spring similar to those at Yellowstone National Park, and a setting where warm water once circulated through shallow subsurface rocks. Once on Mars, the rover will use its on-board instruments to investigate the local geology, to characterize the habitable environments the rover traverses, and to look for evidence of ancient life. Using Earth as a guide, we expect that any Martian life existing at that time was primitive, consisting only of microbes. Truly definitive discovery of microbial biosignatures by instruments on board the rover is unlikely, and can best be undertaken using the full arsenal of terrestrial laboratories. For this reason the Mars 2020 rover will prepare a complete suite of samples for possible return to Earth by a future mission.

Mars 2020 starts with the designs of the remarkably successful Mars Science Laboratory (MSL) and the Curiosity rover. To this platform a suite of very capable new science instruments is being added to explore the structure, chemistry, and mineralogy of the surface all the way from the regional scale down to the microscopic scale. In addition, the mission is developing advanced new capabilities for landing in rugged terrain, for autonomous navigation and science observation, and for robotic coring and caching of samples. These are critical steps towards unleashing the full capabilities of robotic solar system investigation.

The mission will also test new technologies beneficial to future human Mars exploration, most notably a device to demonstrate conversion of carbon dioxide in the Martian atmosphere into oxygen for use as a component of rocket propellant. The mission is currently in the implementation phase (Phase C) with a substantial amount of hardware already completed. Launch will occur in the summer of 2020, with arrival on Mars on February 18, 2021. The rover will be landed using the spectacular sky-crane system pioneered by MSL, and will explore the Martian surface for at least two years. In that period the rover will core and cache at least twenty rock samples, each about the size and shape of a piece of chalkboard chalk. These will be thoroughly documented and placed on the surface, accessible to retrieval by a future mission or even by human explorers. By collecting and caching a diverse suite of high-science-value rock samples, Mars 2020 fulfills the highest priority objectives of the Mars and planetary science communities as described in the most recent Planetary Science Decadal Survey.

Mars 2020 will investigate a planet known with detail sufficient to compellingly address, for the first time, well-posed and profound scientific questions that would forever elude answers from Earthbound study. Going well beyond observations on the Martian surface, return of the cache to terrestrial laboratories would provide future generations of scientists across many disciplines access to samples that would transform our understanding of Mars, the solar system, and life. There is still an enormous amount to learn about Mars, and the deeper we penetrate, the richer the scientific tapestry becomes. Mars 2020 makes the next big step in this decades-long journey, and provides new focus and foundation for human exploration of Mars. It's an honor and a privilege for me to play a part in such a grand and ambitious undertaking.

I look forward to your questions.

[The prepared statement of Dr. Farley follows:]

Statement of

Dr. Kenneth Farley

Mars 2020 Project Scientist
Professor of Geochemistry
California Institute of Technology

before the

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

Thank you for the opportunity to testify today on the Mars 2020 mission.

I have been Mars 2020 project scientist since the mission's inception in early 2013. While I vividly recall my excitement and awe at the first Viking images of the surface of Mars scrolling slowly down a TV screen when I was a child, leading the science team on a future Mars mission was not something I could have pictured until recently. Trained in chemistry and Earth science, I spent most of my career developing lab techniques to interrogate the chemistry of small rock and mineral specimens for what they can tell us about the past. In 2011, I had the opportunity to join the Curiosity science team to do the same kind of work on Mars, specifically to attempt the first radiometric dating of rocks undertaken beyond Earth. The combination of Mars mission experience and an understanding of laboratory analysis of small samples put me in a perfect position to contribute to a mission involving both Mars exploration, and collection of samples that might someday be analyzed on Earth.

Mars 2020 will seek evidence of past life in a fossil Earth-like environment that existed in the first billion years after the dawn of the solar system. This flagship mission will engage many hundreds of scientists and the American public in a very challenging journey through one of the most intriguing landscapes in the solar system and some of the most profound scientific questions of our time.

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It's an honor and a privilege for me to play a part in such a grand and ambitious undertaking. I look forward to your questions.

Biographical Sketch

Ken Farley is the W.M. Keck Foundation Professor of Geochemistry in the Division of Geological and Planetary Sciences at the California Institute of Technology. His research centers on development and application of geochemistry techniques, especially involving isotopes of the noble gases, to a wide range of terrestrial and solar system questions. Specific areas of interest include geochronology of both Earth and Mars, the geochemical evolution of the Earth, and the behavior of noble gases in minerals. He is currently a participating scientist on the Mars Science Laboratory mission and is project scientist for the Mars 2020 Science Rover mission. Farley was born in Los Angeles, California in 1964. He received a Bachelor of Science degree in chemistry from Yale University in 1986 and a doctorate in Earth Science from the Scripps Institution of Oceanography, University of California San Diego, in 1991. He began his professorial career at Caltech, in 1993. He was Chair of the Division of Geological and Planetary Sciences from 2004 to 2014.

Chairman BABIN. Thank you, Dr. Farley.

I now recognize Dr. Pappalardo for five minutes to present your testimony.

TESTIMONY OF DR. ROBERT PAPPALARDO, EUROPA CLIPPER PROJECT SCIENTIST, JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY

Dr. PAPPALARDO. Chairman Smith, Chairman Babin, Ranking Member Bera and other Members of the Committee, I'm delighted to appear before you to describe recent progress in NASA's Europa Clipper mission.

The ice-covered world Europa—moon of Jupiter similar in size to Earth's moon—shows a landscape of cracks, ridges, and jumbled, chaotic terrains indicative of a tumultuous past. The Galileo spacecraft, which orbited Jupiter beginning in the late 1990s, provided images, compositional information, and gravity and magnetic data that point to a remarkable conclusion: Europa likely has a global ocean of liquid water beneath its icy carapace, maintained by tidal flexing and heating. From what we know of the tenacity of life, Europa could be one of the best places in the solar system to search for life beyond Earth.

For these reasons, future detailed investigation of Europa is one of the top priorities for planetary exploration, as expressed in the National Research Council's 2011 Planetary Science Decadal Survey. The Europa Clipper mission responds directly to the Decadal Survey in its top-level goal: explore Europa to investigate its habitability, and in its science objectives to understand Europa's ice shell and ocean, composition, geology, and recent or current activity. The last of these categories includes the possibility that Europa may have active plumes that spew water vapor into space, and which could directly reveal Europa's internal composition and suitability for life. This tantalizing evidence for plumes is provided by the Hubble Space Telescope, searching at the extreme of its detection limits.

In the tradition of the 19th century trading ships for which this mission was recently named, the Europa Clipper will sail past the Jovian moon at a rapid clip as frequently as every two weeks. providing many opportunities to investigate Europa from as close as 16 miles above the surface. During each flyby, the spacecraft will spend just a short time within the challenging radiation environment near Europa. The prime mission plan includes 40 to 45 flybys of Europa from Jupiter orbit, during which the spacecraft will interrogate the moon in unprecedented detail. This will include imaging to understand its geological history; compositional analyses including direct sampling of materials knocked off the surface; ice-penetrating radar to examine the 3D structure of its icy shell; and gravity, magnetic, and plasma measurements to understand its hidden interior and interactions with the Jupiter environment. The mission can also lay the foundation for future exploration of Europa, providing critical global context and scouting potential landing sites for a potential future landed mission.

As its Project Scientist, I represent the science and scientific integrity of the Europa Clipper mission, ensuring it will address the top-level goal and objectives. I first testified before this Committee two years ago, just after NASA had competitively selected nine science instruments for the mission, and had given the green light to begin Phase A, known as mission formulation. In February of this year, NASA completed its second major milestone review, so today we're in Phase B, refining details of how the instruments will achieve the mission's science, and developing preliminary yet detailed design plans for the spacecraft and its subsystems, including the science instruments.

Progress on the instrument suite has been outstanding. Instrument concepts have been reviewed; designs have matured; subsystem vendors are being selected; prototype parts are being built; detectors are being tested; and additional tests are being conducted to ensure robustness against the harsh radiation environment in Europa's vicinity.

Beginning this fall and into next spring, each spacecraft subsystem and each instrument will undergo a preliminary design review to assure that the defined science can be achieved by the instruments and spacecraft in combination. These Phase B reviews are in preparation for the mission to proceed to Phase C around October 2018. It's also at this key decision point that NASA would make a final commitment as to a launch readiness date and baseline mission cost. Then during Phase C, flight hardware would be built.

The members of the mission's science team are working cooperatively together to define the synergistic science which I see as this mission's hallmark. No one instrument can definitively affirm the ocean's existence or tell us convincingly of Europa's composition. Instead, each instrument technique provides a piece of the puzzle, and from the combined science data, Europa scientists will mature a complete picture of how Europa works as a complex system from its submerged rocky core to its ocean to the capping ice shell and surface, to its thin atmosphere, and the surrounding environment of Jovian space.

The clipper ships of the late 19th century were an expression of speed and grace in the golden age of sail. We're now in a golden age of solar system discovery, and the Europa Clipper mission will return to us untold scientific riches.

Thank you, and I look forward to your questions.

[The prepared statement of Dr. Pappalardo follows:]

Statement of

Dr. Robert Pappalardo
Europa Mission Project Scientist
Jet Propulsion Laboratory, California Institute of Technology

before the
Committee on Science, Space and Technology

U.S. House of Representatives

Chairman Smith, Ranking Member Johnson, and other Members of the Committee, I am delighted to appear before you to describe recent progress in NASA's Europa Clipper mission.

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The last of these science categories includes the possibility that Europa may have active plumes that spew water vapor into space, and which could directly reveal Europa's internal composition and suitability for life. This tantalizing evidence for plumes is provided by the Earth-orbiting Hubble Space Telescope, searching at the extreme of its detection limits.

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Thank you, and I look forward to your questions.

Dr. Robert Pappalardo is the Project Scientist for NASA's Europa Clipper Mission at the Jet Propulsion Laboratory, California Institute of Technology. He has also served as the Project Scientist for the Cassini Equinox (first extended) Mission at Saturn, for which he received NASA's Exceptional Service Medal. He has served as a member of the National Research Council's Space Studies Board and as Co-Chair of its Committee on the Origins and Evolution of Life. He received his B.A. in Geological Sciences from Cornell University in 1986, and he obtained his Ph.D. in Geology from Arizona State University in 1994. He His research focuses on processes that have shaped the icy satellites of the outer solar system, especially Europa and the role of its probable subsurface ocean.

Chairman BABIN. Thank you, Dr. Pappalardo.

I now recognize Dr. Elkins-Tanton for five minutes to present her testimony.

TESTIMONY OF DR. LINDA T. ELKINS–TANTON, DIRECTOR AND FOUNDATION PROFESSOR, SCHOOL OF EARTH AND SPACE EXPLORATION, ARIZONA STATE UNIVERSITY; PRINCIPAL INVESTIGATOR, NASA PSYCHE MISSION

Dr. ELKINS-TANTON. Chairman Babin, Chairman Smith, Ranking Member Bera, and the Members of the Committee, thank you so much for the opportunity to speak today. Today I'll be testifying in my personal capacity.

Any discussion of NASA's planetary science program would be incomplete without also talking about the balance between flagships and smaller planetary missions, and so today I'm going to talk about three things. I'm going to talk about the newly selected Psyche mission, I'm going to talk about portfolio balance, and I'm going to talk about our inevitable space future.

I am the Principal Investigator of the Psyche mission, which in January was selected as the 14th in the NASA's Discovery program. The spacecraft is scheduled to launch in August of 2022 to rendezvous with the asteroid Psyche in January of 2026, and to orbit Psyche for 22 months. Psyche is a metal world with a diameter about the same as the width of Massachusetts and with a surface area larger than the area of Texas. Humankind has explored rocky worlds and we have explored icy worlds and we have explored worlds covered with gas but we have never before explored a metal world. This is a first.

We think that Psyche is the core of a small early-formed planet that was bombarded in the early solar system and had its rocky exterior knocked off so that only its metal core remains showing today. Computer models of planetary formation indicate that this is rare, and indeed, Psyche is the only large, round metal object in our solar system, so it's not just unique, it's improbable.

The science we hope to achieve in the mission is first to determine whether indeed Psyche is a core, or if it is some previously undiscovered kind of material. We'll be comparing what we learn at Psyche to models of the Earth's core to better understand that unreachable part of our own planet. And for the first time, we'll be investigating the morphology of a metal body. What do craters into metal look like? Could Psyche have glittering cliffs of metal and green pyroxene crystals? We don't know yet. No one knows yet. At Psyche, we will also take the first steps toward our space resource future because we're pretty confident that Psyche almost entirely consists of iron, nickel, copper, and a variety of trace metals.

Now, I strongly support the Planetary Decadal Survey's conclusion about the necessity for having a balanced mission portfolio combining small and mid-sized missions on a regular tempo with flagships. Tempo is critical. Tempo maintains our workforce and it also saves our institutional memory, but each size of mission comes with its own challenges and its own its own advantages. For smaller missions like Psyche, usually keeping costs down and keeping risk down means that we're going to use trusted high-heritage components whereas flagship missions give us the opportunity for innovation and new technology development, and we need both of those things. We need our trusted technology today and we need new technology for the future.

Flagship missions can also engage a broader swath of the community through competed calls for instruments. These calls can bring new groups onto missions that would otherwise not be involved but then the project scientist has the challenge of organizing and uniting otherwise disconnected sub-teams. It's an interesting challenge. In fact, all lead scientists have to build, inspire and lead large interdisciplinary teams, and normally engineers and scientists are not taught these skills, so we are trying to change that at ASU now.

Exploration is a human imperative. It is stamped on our DNA, and space is the future of exploration for humankind. Every time we do this most extreme of technological miracles and we send a rocket off of our Earth to make discoveries in space, we encourage people all around the world to make a bolder step in their own lives and in their own communities. So space exploration is therefore an opportunity for us to create a better educated, more united society.

At ASU I'm also co-chair with President Michael Crow of our new Interplanetary Initiative. In this initiative, we're bringing together not just the technological but the educational and the social aspects that we need for our space future, and indeed, education is the single most critical thing for humanity's future. Both at ASU and at our startup, Beagle Learning, we are working on next-generation learning. We need to produce a critical mass of people who are attracted to the unknown, who are learning how to ask better questions, who are willing to pursue answers through partial solutions, and who know how to build teams and to lead. All this ideation is initiated by the vision and the process of NASA, and in fact, space exploration will bring us to a better future here on Earth as well as eventually on the moon and Mars and beyond.

Thank you very much.

[The prepared statement of Dr. Elkins-Tanton follows:]

U.S. House of Representatives
Committee on Science, Space, and Technology, Subcommittee on Space
July 18th, 2017, "Planetary Flagship Missions: Mars Rover 2020 and Europa Clipper"

Dr. Linda T. Elkins-Tanton
Director and Foundation Professor, School of Earth and Space Exploration
Principal Investigator, NASA Psyche Mission
Co-chair, Interplanetary Initiative
Arizona State University
Co-founder, Beagle Learning LLC

Chairman Babin, Ranking Member Bera, and Members of the House Committee on Science, Space, and Technology, Subcommittee on Space:

Thank you for allowing me to speak today. I am testifying in my personal capacity. Though much of today's hearing is on the Mars 2020 and Europa flagship missions, a discussion of NASA's planetary science program would be incomplete without also talking about the balance between them and smaller planetary projects.

The Psyche Mission

I am the Principal Investigator of the NASA Psyche mission, which was selected as the 14th in the Discovery program within NASA's Science Mission Directorate. The Psyche mission is scheduled to launch in August 2022, rendezvous with the asteroid Psyche in January 2026, and orbit it for 22 months.

Psyche is a metal world with diameter about the width of Massachusetts, and surface area greater than the state of Texas. We have explored rocky worlds like Mars and the Moon, and icy worlds like Ceres, and worlds with gas surfaces like Jupiter and Saturn, but we have never explored a metal world. Here I will make a brief description of the Psyche mission and its purpose.

Beneath our feet is 1,800 miles of rock, and then the Earth's core, which is primarily iron and nickel metal. Venus, Mars, Mercury, and the Moon have similar differentiated structures, with rock overlying a metal core. The Earth's core is the source of our magnetic field, which protects us from radiation and helps to shield our atmosphere from erosion by the solar wind. The metal core of a terrestrial planet, therefore, is central to a planet's habitability, and yet we have never seen or sampled our core. We can only study it remotely through seismic waves and heat flow measurements. The pressure at the core is three million times surface atmospheric pressure, and its temperature is 10,000F; we are never going to our core.

The leading hypothesis for the formation of Psyche is that it is the core of a small early-formed planet that was stripped of its rocky exterior by multiple hit-and-run impacts in the early solar system. The period of intense impacts that either broke new small planets apart or accreted them together to form the planets we have today was just the first five million years after the first solids formed in our solar system, the equivalent of the first minute and a half if our solar system's 4.56 billion years were scaled to 24 hours.

Computer models of planetary formation indicate that it was possible, but rare, for a single small body to experience multiple stripping impacts with no additive impacts. Indeed Psyche is the only large, round metal world in our solar system: it is both unique and improbable.

The science objectives of the mission are to determine whether Psyche is a core, or if it is material with a previously undiscovered origin; to determine the relative ages of regions of its surface; to compare its composition to models for the Earth's core; and, for the first time, to characterize the morphology of a metal world. What do craters into metal look like? Could Psyche bear glittering cliffs of metal and green pyroxene crystals?

The Psyche mission is led by Arizona State University and managed by NASA's Marshall Space Flight Center. NASA's Jet Propulsion Laboratory is responsible for mission management, operations, and navigation. The spacecraft's solar-electric propulsion chassis will be built by Space Systems Loral, a new partner for NASA that brings special economies as an experienced commercial vendor. The spacecraft's payload comprises an imager from ASU and Malin Space Science Systems, a magnetometer from UCLA and MIT, and a gamma-ray and neutron spectrometer from the Applied Physics Laboratory. The Psyche mission is also scheduled to carry an important technology demonstration, the Deep Space Optical Communications instrument, to test laser communications between deep space and the Earth.

By making this voyage to a metal world, our nation is creating another first in space exploration history. This concept has captured the imaginations of people around the world: in the few months since selection we have been featured in over 100 articles and news stories, with outlets including the *Washington Post*, *The New York Times*, and the *Wall Street Journal*.

Exploration is a human imperative. It is stamped into our DNA. And we have a space future, as a society, as a species. Psyche raises the level of excitement with a new kind of world and a voyage of pure exploration. We are seeing and measuring things that have neither been seen nor measured by humankind before.

We will learn not just about the processes and materials that create habitable planets, we will also take the first steps toward our space resource future: we believe that Psyche consists almost entirely of iron, nickel, copper, and a variety of trace metals. This confluence of motivations, from understanding the science of planetary origins, to the structure and composition of the Earth's deep interior today, to the first investigations into a critical future space resource, make Psyche an especially interesting target.

NASA Mission Portfolio Balance

The Psyche mission is P.I.-led. The science is highly focused and the spacecraft can be produced from high-heritage components, allowing a relatively quick timeline, keeping the tempo of exploration up.

Tempo is critical – we need to exercise, maintain, and build our precious space engineering and science workforce. Fallow times translate directly into job loss, loss of institutional memory, and loss of the ability to do the great space exploration feats we are so rightly proud of. Thus, Discovery and New Frontiers missions and their planned regularity of selection are critical not just to producing new discoveries, but to maintaining our ability to move into our space future.

All missions engage students in science and engineering, and on Psyche, we also engage student interns in education, outreach, and art. Maximizing the opportunities for younger students to get involved with missions is a goal we are grappling with. We would like to enable more students from universities without active space science and engineering faculty to participate; this is a challenge for NASA and for all educational institutions.

To balance the relatively smaller P.I.-led missions, NASA manages large flagship missions. Some great challenges in understanding our universe are too large for the tempo and size of a P.I.-led mission. Missions facing significant technology development challenges or complex measurements demanding a large payload require more direct leadership from NASA.

Technology development is critical for progress, but it is expensive and time-consuming, and must be specifically encouraged and planned for. Without explicit funding for technology development, the low-risk strategy of using high-heritage technologies will prevail; we need both solid high-heritage technology and innovation for the future. Further, flagship missions are a perfect platform for combining the goals of robotic and human space exploration, as, for example, the MOXIE experiment on the Mars 2020 rover.

Flagship missions also engage a broader swath of the community, through competed calls for instruments, for example, which P.I.-led missions generally do not employ. This more equal opportunity has a greater possibly of bringing new groups onto missions, but the project scientist then has the challenge of organizing and uniting disconnected subteams.

A challenge to all missions is the transition required for the lead researcher to move from a traditional academic or research position to organize, inspire, and lead large interdisciplinary teams. These skills are not generally taught to scientists or engineers. We are working at ASU to change this, and to produce a new generation of scientists and engineers with the skills to lead and thus to solve bigger problems, to wield the multiple capabilities of an interdisciplinary team, and to move us faster into a positive future.

Thus, I strongly support the Planetary Decadal Survey's conclusions about the advantages, indeed the necessity, of having a balanced portfolio including small and medium P.I.-led missions on a regular tempo as well as flagship missions.

The Imperative of our Space Future

At its heart, space exploration is far more than the privilege and right of a developed country. It is the future of exploration for humankind, and also an opportunity – an opportunity to build a better educated, better trained, more united society. An opportunity to create the positive future we envision. The size and influence of these projects provides the leverage we need to inspire education, to stimulate innovation, to motivate society. Every time we do the most extreme of human technological accomplishments by sending a spacecraft off our Earth to make new discoveries, we inspire the people around the world to take a bolder step in their own lives and in their own communities.

At ASU I am also co-chair with President Michael Crow of our new Interplanetary Initiative. In this initiative, we are bringing together the societal, educational, and technical capabilities and concepts required for our space future. The university is creating an exploration model as a methodological approach to learning. We need to produce a critical mass of people who are attracted to the unknown, learn how to ask good questions, are willing to pursue answers with fractional steps of progress, and know how to be leaders and build teams.

All this ideation is initiated by the processes and vision of NASA. Space exploration inspires and motivates us to act not just in space, but also on Earth. NASA's programs exist on multiple scales, for good reason, to invigorate science, education, technology development, and the STEM workforce.

Biography
Dr. Linda T. Elkins-Tanton

Director and Foundation Professor, School of Earth and Space Exploration
Principal Investigator, NASA Psyche Mission
Co-chair, Interplanetary Initiative
Arizona State University
Co-founder, Beagle Learning, LLC

Lindy Elkins-Tanton is the director of the School of Earth and Space Exploration at Arizona State University and she is the Principal Investigator of the Psyche mission, selected as part of NASA's Discovery program.

Her research includes theory, observation, and experiments concerning terrestrial planetary formation, magma oceans, and subsequent planetary evolution including magmatism and interactions between rocky planets and their atmospheres. She also promotes and participates in education initiatives, in particular, inquiry and exploration teaching methodologies, and leadership and team-building for scientists and engineers.

She has lead four field expeditions in Siberia, as well as participated in fieldwork in the Sierra Nevada, the Cascades, Iceland, and the Faroe Islands.

Elkins-Tanton received her B.S. and M.S. from MIT in 1987, and then spent eight years working in business, with five years spent writing business plans for young high-tech ventures. She then returned to MIT for a Ph.D. Elkins-Tanton spent five years as a researcher at Brown University, followed by five years on MIT faculty, before accepting the directorship of the Department of Terrestrial Magnetism at the Carnegie Institution for Science. In 2014 she moved to the directorship at Arizona State University.

She serves on the Standing Review Board for the Europa mission, and served on the Mars panel of the Planetary Decadal Survey and on the Mars 2020 Rover Science Definition Team.

Elkins-Tanton is a two-time National Academy of Sciences Kavli Frontiers of Science Fellow. In 2008 she was awarded a five-year National Science Foundation CAREER award, and in 2009 was named Outstanding MIT Faculty Undergraduate Research Mentor. In 2010 she was awarded the Explorers Club Lowell Thomas prize. The second edition of her six-book series The Solar System, a reference series for libraries, was published in 2010 and the book *Earth*, co-authored with Jeffrey Cohen, was published in 2017. Asteroid (8252) Elkins-Tanton was named for her. In 2013 she was named the Astor Fellow at Oxford University, and in 2016 she was named a Fellow of the American Geophysical Union.

Chairman BABIN. Thank you, Dr. Elkins-Tanton.

Now I'd like to recognize Dr. McKinnon for five minutes for your testimony.

TESTIMONY OF DR. WILLIAM B. MCKINNON, CO-CHAIR, NATIONAL ACADEMY OF SCIENCES, COMMITTEE ON ASTROBIOLOGY AND PLANETARY SCIENCE; PROFESSOR OF EARTH AND PLANETARY SCIENCES, WASHINGTON UNIVERSITY IN ST. LOUIS

Dr. MCKINNON. Good morning, Mr. Chairman, Members of the Committee.

So I'm here today because I'm a Co-Chair of the Committee on Astrobiology and Planetary Sciences, or CAPS, for the National Academies, but I wish to say that my testimony today is my own and is not an official report from CAPS or the Academies. Nevertheless, I hope you find my remarks useful.

So I'd like to focus on the Planetary Science Decadal Survey and its relation to flagship and other planetary missions. Obviously decadal surveys are carried out about every ten years for various space science disciplines and the Committees and the panels that carry out the decadal are drawn from the broad community associated with the discipline in question. Decadal survey recommendations to the government play a critical role in defining our country's agenda in a given science area for ten years or even longer.

Now, the Planetary Science Decadal Survey was tasked in particular, among many things, to create a prioritized list of flight investigations because missions lie at the heart of planetary exploration. Such a prioritization is based first and foremost on science, especially science per dollar, but also on programmatic balance among mission targets and balance among mission types—small, medium and large. Indeed, a balanced mix of discovery, new frontiers and flagship missions enable both a steady stream of new discoveries and the capability to address larger challenges such as sample return missions or outer solar system exploration.

Prioritization also considers technological readiness, the availability of trajectory opportunities, understanding of cost and technological risk, and the fiscal climate. Anyway, these prioritizations take in the sense that decadal surveys succeed because the consensus they represent is compelling.

Now, in terms of science, increasingly central to NASA's exploration of the solar system is the emerging science of astrobiology, prominent examples being the scientific program of the Curiosity Mars Rover, the Mars 2020 rover, the development of the Europa Clipper mission, and the planning for the potential future landing on the surface of Europa and the inclusion of ocean worlds in the recent new frontiers call.

Indeed, in the most recent Planetary Decadal Survey, astrobiology was a driving scientific rationale for the two top mission recommendations now being implemented as Mars 2020 and Europa Clipper. Now, my personal assessment, and as the CAPS leadership has previously reported to the Space Studies Board, is that NASA's Planetary Science Division is doing well and the Decadal Survey's priorities and recommendations are being pursued. Mars 2020 and Europa Clipper in particular are, I believe, responsive to the Decadal Survey in science and cost.

Now, regarding NASA's plans to explore Europa, CAPS, as well as the ongoing Academies' planetary mid-term review will continue to consider the aspects of—consider the impacts of the evolution of this program. Presently, NASA has been directed to add a lander to the Europa exploration program. The development of any large mission like that is of course a programmatic challenge and can have unwelcome or worse effects on a broad cost-contained program. But this challenge must be balanced against the scientific opportunity afforded by the promise of addressing one of the greatest of scientific questions: is there extant life beyond Earth?

As I said, these are all issues I expect CAPS will continue to consider and will also be surely considered by the next decadal as well.

So to finish up, Mr. Chairman, as a second grader I watched the liftoff of John Glenn and Friendship 7 in our auditorium, and as a teenager at home I watched Neil Armstrong walk on the moon. Over the past 60 years, I have seen NASA's exploration of the solar system from Mercury out to Pluto and beyond, revolutionize our conception of ourselves and our planet, but I believe given our ongoing discoveries and characterization of planets around other stars, thousands of them we know about now, and the very real possibility of detecting extant life in our solar system that we are approaching an even greater revolution, a true paradigm shift in our understanding of our place and our destiny in the universe.

Thank you very much.

[The prepared statement of Dr. McKinnon follows:]

Testimony of

Dr. William McKinnon,

Washington University in St. Louis, Saint Louis, Missouri

before the

Committee on Science, Space, and Technology, Subcommittee on Space

U.S. House of Representatives

July 18, 2017

Chairman Babin, Ranking Member Bera, and Members of the House Committee on Science, Space, and Technology, Subcommittee on Space:

Thank you for the opportunity to appear before you today at this important hearing. I speak to you today as a scientist with more than 40 years of spaceflight related research, largely funded by grants from NASA's planetary science division. I also have the honor to serve as Co-Chair of the Committee on Astrobiology and Planetary Sciences (CAPS) of the National Academies of Sciences, Engineering and Medicine. However, I want to note that my testimony today is my own and should not be taken as reflecting any consensus views or advice from CAPS or the

National Academies. The views I express today are based on my personal assessment of information and presentations made available to CAPS as it has been monitoring the implementation of the planetary science decadal survey. CAPS is one of five subcommittees of the Academies' Space Studies Board—each of which is charged to assist the federal government in integrating and planning programs in space sciences by providing advice on the implementation of decadal survey recommendations. I have the honor of co-chairing CAPS along with Dr. Christopher House of The Pennsylvania State University. We are particularly honored to chair this important committee at a time when it embarks on its work with a new charter from the Academies that will enable our committee to issue short, topical reports that will provide guidance to federal agencies that support astrobiology and planetary science research. The scope of CAPS spans space-based and supporting ground-based planetary research within our own planetary system, including, for example, geosciences, atmospheres, particles and fields of planets, moons, rings, and small bodies, as well as astrobiology, sample analysis, planetary astronomy, and planetary protection. The CAPS's scope also includes appropriate cross-disciplinary areas and consideration of budget and programmatic aspects of the implementation of the decadal survey.

Chairman Babin, I would like to thank you and the committee for giving me the opportunity to present to you today some personal perspectives on the implementation of the most recent 2011 decadal survey in planetary sciences—"Vision and Voyages for Planetary Sciences in the Decade 2013-2022." Because others this morning will give the committee comprehensive reports on the status of the Mars 2020 and Europa Clipper missions, my testimony will focus on some of the driving principles that underpinned the decadal survey's recommendations for these missions and other elements of the planetary science program at NASA.

It is also worth noting that as we meet today, an ad hoc committee (not CAPS) has been established by the Academies on the request of NASA to review the response of NASA's Planetary Science program to the 2011 decadal survey. That committee's work is well underway and it is charged to recommend any actions that could be taken to optimize the science value of the planetary science program including how to take into account emergent discoveries since the publication of the decadal survey in the context of current and forecasted resources available to NASA. The midterm review committee is also being asked to provide guidance about implementation of the decadal's recommended mission portfolio and decision rules for the remaining years of the current decadal survey, but it is specifically charged to not "revisit or redefine the scientific priorities or mission recommendations from [Vision and Voyages]." The midterm study is also undertaking the review of the Mars exploration architecture called for by the Congress in the most recent NASA authorization legislation. I am also pleased to report that NASA and the Academies have also acted expeditiously to initiate the other two studies called for in that legislation on science strategies for exoplanet discovery and characterization and for astrobiology and the search for life. All three of these studies will provide critical inputs into the upcoming decadal surveys in astronomy and astrophysics and in planetary sciences that are expected to get underway in December 2018 and the Spring of 2020, respectively.

Mr. Chairman, I would like first to remind us all what a National Academies decadal survey in space science is supposed to be. Decadal surveys are carried out with a cadence of approximately 10 years for each space science discipline. The National Academies have conducted decadal surveys for more than 50 years, since astronomers first developed a strategic plan for ground-based astronomy in the 1964 report "Ground-Based Astronomy: A Ten-Year Program." The committees and supporting panels that carry out the decadal surveys are drawn from the broad community associated with the discipline in review, and these volunteers comprise some of the nation's leading scientists and engineers. The Academies' decadal surveys are notable in their ability to sample thoroughly the research interests, aspirations, and needs of a scientific community. Through a rigorous process lasting about 2 years, a primary survey committee and "thematic" supporting panels of community members construct a prioritized program of science goals and objectives and define an executable strategy for achieving them. Decadal survey reports to agencies and other government entities play a critical role in defining the nation's agenda in that science area for the following 10 years, and often beyond. Eleven decadal surveys have now been completed and in 2015 the Academies released a so-called "survey of surveys" report—"The Space Science Decadal Surveys: Lessons Learned and Best Practices". Mr Chairman, I would recommend to you and the members of the committee that report's accounting of lessons learned on the decadal process. You will see therein a reflection of what I believe is the widely-held belief of the space science research community that the decadal surveys have been a model in the world of science for how community consensus can be achieved—on science goals and on a program of activities to achieve them.

Mr. Chairman, I would like to return for a moment to the science of astrobiology and in particular the search for life. CAPS has collaborated with the Academies' Committee on Astronomy and Astrophysics to assemble a committee drawn from the planetary and astronomy research communities under the leadership of Dr. James Kasting, also a CAPS member, to organize a workshop held in December 2016 on facilitating an expert dialogue on the current status of extraterrestrial life detection and related issues. That workshop considered important questions such as:

- What is our current understanding of the limits of life and life's interactions with the environments of planets and moons?
- Are we today positioned to design, build and conduct experiments or observations capable of life detection remotely or in situ in our own solar system and from afar on extrasolar worlds?
- How could targeted research help advance the state of the art for life detection, including instrumentation and precursor research, to successfully address these challenges?

A proceedings report that will document the workshop, including summaries of individual presentations and ensuing discussions will be published by the National Academies very shortly and will provide invaluable input into the exoplanet and astrobiology studies now getting underway and which are of such interest to this committee. More information on the workshop and the current state of the challenge of the science of the search for life can be found in Dr. Kasting's testimony to the Committee on Science, Space and Technology on April 26, 2017.

Mr. Chairman it is also worth noting that astrobiology is increasingly at the heart of our exploration of the solar system. CAPS has heard about these exciting science opportunities through NASA, opportunities such as: the scientific program of the *Opportunity* and *Curiosity* rovers that are roaming the martian surface and the 2020 rover that is under development; the Psyche and Lucy missions that will provide context to our understanding of the origin of habitable worlds and the formation of organic-rich planetary bodies, respectively; the development of the Europa Clipper mission and the planning for a potential future landing on the surface of Europa; and of course the inclusion of Ocean Worlds in New Frontiers 4.

Indeed in the Vision and Voyages decadal survey, astrobiology was at the heart of the scientific rationale for two of the top large flagship mission recommendations. The compelling science that drove the survey to recommend the concepts "Mars Astrobiology Explorer-Cacher Descope"—now being implemented as Mars 2020—and "Jupiter Europa Orbiter Descope"—now being implemented as Europa Clipper— were:

- Perform in situ science on Mars samples to look for evidence of ancient life or prebiotic chemistry; and collect, document, and package samples for future collection and return to Earth; and
- Explore Europa to investigate its habitability.

Since the release of the decadal survey report in 2011, CAPS has been receiving frequent reports on the implementation of these priorities by NASA. Since then the committee co-chairs have reported to the Space Studies Board at its semi-annual meetings and repeatedly at the most recent SSB meetings. I, Chris House and our predecessor co-chairs have reported to the board our personal assessment that the Planetary Science Division is in a good state and the decadal's priorities are being pursued. In particular we have noted that the Mars 2020 astrobiology/sample-caching rover mission continues its development toward a 2020 launch; the Europa Clipper mission to explore Europa and investigate its habitability is in Phase B (design phase); two Discovery-class missions have been selected (Psyche, M-[or metal]-type asteroid orbiter and Lucy, multi-Trojan asteroid flyby), and another one is in extended Phase A (NEOCam) development; and finally the next New Frontiers class mission proposals were submitted April 28th of this year and are currently being assessed.

Mr. Chairman, one of the most exciting possibilities in space science today is the opportunity we have to find evidence for extant, or extinct, extraterrestrial life in the solar system. In that regard, our current suite of astrobiology missions is key to the future of planetary science. The opportunity to explore Europa in detail is therefore all the more exciting. With this in mind, I am sure CAPS—and indeed the planetary midterm review committee—will continue to consider the impacts of the evolution of NASA's plans to explore Europa. The multiple flyby Europa Clipper mission is, I believe, highly responsive to the decadal survey in science and cost. Indeed it is my personal view, and one that I have expressed in other forums (such as when I was chair of the Outer Planets Assessment Group—a group supported by NASA to provide community input to Dr. Green and the Planetary Science Division), that the Europa Clipper mission is in many ways superior to the original Jupiter Europa orbiter mission considered by the decadal. The Clipper design solves many thorny engineering problems, which I can discuss if you wish. Important from a CAPS perspective, the evolution of the Jupiter Europa orbiter to the Europa Clipper is in my view just the sort of outcome we would hope for as the result of decadal recommendations.

I would now like to address the possibility of a Europa lander. No mission to land on Europa was proposed to the survey committee and panels as the decadal was being conducted. It is, however, worth noting that two Europa lander concepts were briefly discussed, but not prioritized, in the 2003 decadal survey for planetary science, "New Frontiers in the Solar System: An Integrated Exploration Strategy." Today we all know that NASA has been directed to add a lander to the overall Europa exploration program and to launch the Europa Clipper on a Space Launch System (SLS) vehicle. Mr. Chairman, I am sure you will recognize that a key concern for the decadal survey panels and steering committee was to understand the risks associated with cost and affordability, as well as risks associated with complexity and the state of technology development. There is, in addition, the programmatic challenge posed to the overall planetary science program by the development of another large, strategic mission so close in time with Mars 2020 and Europa Clipper. That said, there is also the scientific opportunity afforded by landing on Europa, the opportunity to address one of the greatest scientific questions—is there life, extant life, beyond the Earth? These are all issues that I expect CAPS will continue to consider and on which we may issue future reports as we consider our task to provide advice on the implementation of the decadal survey. I also expect the midterm review committee's report that will be published in the Spring of 2018 will also consider these opportunities and challenges. Understanding these issues is key to pursing another key goal of the Vision and Voyages decadal survey—maintaining a balance across the whole planetary sciences program at NASA.

As noted in the decadal, the statement of task for the survey called for the creation of a prioritized list of flight investigations for the decade 2013-2022. A prioritized list implies that the elements of the list have been judged and ordered with respect to a set of appropriate criteria.

Four criteria were used by the decadal steering committee as it made the difficult choices among a suite of very compelling science opportunities across the breadth of solar system exploration. The first and most important was science return per dollar. Science return was judged with respect to the key science themes, namely:

- Building new worlds—understanding solar system beginnings,
- Planetary habitats—searching for the requirements for life, and
- Workings of solar systems—revealing planetary processes through time.

The second criterion was programmatic balance—striving to achieve an appropriate balance among mission targets across the solar system and an appropriate mix of small (e.g., Discovery class), medium (e.g., New Frontiers class), and large (flagship) missions. The other two criteria were technological readiness and availability of trajectory opportunities within the 2013-2022-time period. Costs and technical risks were estimated via the independent Cost and Technical Evaluation (CATE) process developed by the Aerospace Corporation for the National Academies. In addition, the decadal recommendations were placed into a context of likely resources available, that is, the Planetary Science Division's budget for the decade in question. A nominal projected budget, as well as both an enhanced and a more cost-constrained budget for the decade were considered.

The decadal survey went on to recommend that NASA's suite of planetary missions for the decade 2013-2022 should consist of a balanced mix of Discovery, New Frontiers, and large missions, enabling both a steady stream of new discoveries and the capability to address larger challenges such as sample return missions and outer planet exploration. The program recommended in the decadal was designed to achieve such a balance. To prevent the balance among mission classes from becoming skewed, the decadal noted that it is crucial that all missions, particularly the most-costly ones, be initiated with a good understanding of their probable costs. The CATE process was designed specifically to address this issue by taking a realistic approach to cost estimation—albeit of early proof-of-concept designs. It is also important that there be an appropriate balance among the many potential targets in the solar system. Achieving this balance was one of the key factors informing the recommendations for medium and large missions presented in the decadal. These considerations also led to the decadal recommending among its flagship class of missions, investigations of Uranus and Neptune—targets that represent a wholly distinct class of planet, the so-called ice giants. The ice giants are one of the great remaining unknowns in the solar system, the only class of planet that has never been explored in detail, and one tied directly to the plethora of exoplanet discoveries. The decadal recommended that the third-highest-priority flagship mission was the Uranus Orbiter and Probe mission and that, if the budget allowed, it should be initiated the exploration of the ice giants in the decade 2013-2022 even if both of what are now Mars 2020 and Europa Clipper take place.

I note here that NASA takes such recommendations seriously. An ice giant mission study, put together by a science definition team, has recently been released by NASA. Similarly, a Europa lander mission study, put together by its own science definition team, has also been released. Both of these reports are, in my view, beautiful and visionary documents which fully capture the scientific promise and excitement of NASA's exploration of the solar system. And such reports can also be regarded as "pre-next-decadal," in the sense that they can feed forward to the deliberations of the next planetary science decadal survey.

Regarding decadal recommendations, issues of balance across the solar system and balance among mission sizes are related. For example, it is difficult to investigate targets in the outer solar system with small or in some cases even medium-class missions. Though I note here the successful reconnaissance of the Pluto system by New Horizons and ongoing, focused studies of Jupiter by the Juno orbiter, which just flew over the Great Red Spot (pictures of which you may have seen). These two missions are part of NASA's medium-class, New Frontiers portfolio. Nevertheless, some targets are ideally suited to small missions. The decadal's recommendations reflect this fact and implicitly assume that Discovery missions will address important questions whose exploration does not require the capability provided by medium or large missions.

A scientifically appropriate balance of solar system exploration activities must be found by selecting the set of missions that best addresses the highest priorities among the overarching science questions associated with the three crosscutting science themes identified by the comprehensive community-consensus-building process that the decadal survey represents. As we in CAPS consider the implementation of the decadal survey's recommendations, we will do so in accordance with this principle.

Mr. Chairman, as a second grader I watched the liftoff of John Glenn and Friendship 7 and as a teenager I watched Neil Armstrong walk on the Moon. Over these past three score years NASA's exploration of the solar system from Mercury out to Pluto and beyond has revolutionized our conception of ourselves and our planet. But I believe, given our ongoing discoveries and characterization of planets around other stars and the very real possibility of detecting extant life in an ocean world in the outer solar system, that we are approaching an even greater revolution in our understanding of our place in the Universe. Without doubt, NASA's planetary science program has the real and present potential of leading to a true paradigm shift in human knowledge and awareness as we continue to explore the origins of our solar system and the life it sustains.

In conclusion, I thank you for giving me the opportunity to testify today and welcome any questions you may have.

William B. McKinnon is a Professor of Earth and Planetary Sciences and a member of the McDonnell Center for the Space Sciences at Washington University in Saint Louis. He received his S.B. in Earth and Planetary Sciences from MIT in 1976 and his Ph.D in Planetary Science and Geophysics from Caltech in 1981. His research concerns the structure, origin, evolution, tectonics, and bombardment histories of outer planet satellites and Kuiper belt objects, and fundamentals of impact cratering throughout the solar system. He currently teaches The Solar System, Planetary Geophysics and Dynamics, Planetary Geology, Advanced Planetary Geology: Ice Worlds, and Freshman Seminar: Planetary Exploration.

McKinnon is a Science Team member of the *New Horizons* mission to Pluto and the Kuiper belt, where he serves as a Deputy Lead for the Geology, Geophysics and Imaging (GGI) Theme Team. He is also a Science Team member of the Radar for Icy Moon Exploration (RIME) instrument for ESA's *Jupiter Icy Moons Explorer* (JUICE) mission, and a Co-Investigator with the REASON radar and MASPEX mass spectrometer instruments for NASA's forthcoming *Europa Clipper* multiple flyby mission. In addition, he is currently a Co-investigator for its Solar System Workings program, and a Distinguished Visiting Scientist at the Caltech Jet Propulsion Laboratory (JPL).

McKinnon has served twice on the Committee on Lunar and Planetary Exploration (COMPLEX/NRC) and on numerous NASA review panels, was a member of NASA's Outer Planets Science Working Group (OPSWG) and Solar System Exploration Subcommittee (SSES), and is a past Chair of the Outer Planets Assessment Group (OPAG) and former member of the Planetary Science Subcommittee (PSS) for NASA; he now serves as a co-chair of CAPS (Committee on Astrobiology and Planetary Science) for the Space Studies Board of the National Academies (NAS). He was an Associate Editor for the *Journal of Geophysical Research–Planets*, a Consulting Editor for *Icarus*, and co-chaired the Scientific Organizing Committee of the 2001 DPS meeting. He co-edited the book *Jupiter –The Planet, Satellites, and Magnetosphere* for Cambridge University Press, and *Europa* for University of Arizona Press. He also served on the JIMO (Jupiter Icy Moons Orbiter) Science Definition Team, the NRC-NAS Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion, the Science Panel of the 2007 NASA Flagship Mission Studies Review, and chaired the Science Panel of the 2008 NASA Flagship Mission Studies Review. He recently became a Co Editor-in-Chief for *Earth and Planetary Science Letters*.

McKinnon has received three Group Achievement Awards from NASA, asteroid 9526 Billmckinnon is named for him, and in 2014 he received the G.K. Gilbert Award from the Planetary Geology Division of the Geological Society of America (GSA), which is given for outstanding contributions to the solution of fundamental problems in planetary geology. He is a past Chair of the Division for Planetary Sciences of the American Astronomical Society (DPS), a past-President of the Planetary Sciences section of the American Geophysical Union (AGU), and is a member of Phi Beta Kappa (MIT). He is a Fellow of the American Association for the Advancement of Science (AAAS) and of the Geological Society of America (GSA).

Chairman BABIN. Thank you, Dr. McKinnon. All fascinating testimonies. I really appreciate it. The Chair now recognizes himself for five minutes.

Dr. Green, in the near future, NASA's Planetary Science Division may be running three flagship missions at the same time: the Mars rover for launch in 2020, the Europa Clipper for launch in 2022, and potentially a Europa lander for launch in the 2024 time frame. I greatly support this investment and NASA's renewed focus on deep space exploration. At the same time, from an acquisition perspective, this is a great deal of work. What is NASA doing to address the risks of cost and schedule slips associated with this cadence of flagship missions?

Dr. GREEN. Planetary Science I think has tackled a number of those topics and is doing quite well because we started to implement a couple very important and new procedures. Typically, strategic missions in the past based on a science rationale that's almost at any cost. In Planetary Science, we begin the—we have begun the process in particular with Mars 2020 to have a cost-constrained environment. As was recognized on the Planetary Decadal, both the Mars Cacher and the Europa Clipper were unaffordable, and we took on a process early in this decade to begin to determine what science we can do at that reasonable cost. We're leveraging on Mars 2020 the architecture for Curiosity. We've done a lot of work on the planning of the Europa Clipper where we're looking at descope options, and so some of these processes are incredibly important for us to follow through on.

Chairman BABIN. Okay. Thank you very much.

And now the next question to Dr. McKinnon. To what extent do the Mars Rover 2020 and Europa Clipper missions align with the Decadal Survey recommendations?

Dr. MCKINNON. Well, the original survey considered two flagship-class missions, Mars astrobiology Explorer-Cacher and a Europa Jupiter orbiter mission, a mission to orbit Europa itself, and in both cases the Decadal Survey concluded based on a very detailed cost and technical evaluation that these missions were probably too expensive to be carried out in the decade in question. And so basically they said these were our priority missions but they needed to be descoped. They needed to be reduced in cost and perhaps reduced—and certainly reduced in risk. And in both cases, I think they've done that. As an example, the Europa mission doesn't orbit Europa anymore but it orbits Jupiter but repeatedly passes by Europa dozens of times and basically recovers all of the science, and in fact, in my own view actually does an even better job because it avoids so much of the radiation that's near Jupiter and it allows in its long looping orbits around Jupiter that Dr. Pappalardo can tell you about, it can radio back all the data that it collects every time, and it does it within a very reasonable cost cap.

Chairman BABIN. Thank you very much.

Now, I also would like to ask Dr. Farley and Dr. Pappalardo, the exploration of Mars and Europa are inspiring and truly amazing. As Project Scientists for Mars Rover 2020 and the Europa Clipper, can you share with us what excites you about these exploration efforts, and what are the greatest scientific discoveries that you're hoping to achieve?

Dr. FARLEY. Well, I think the most exciting thing about Mars is that, as I mentioned in my testimony, the surface of Mars is—carries a rock record from a time period which is completely obliterated on Earth. There is no substantial rock record that is older than about 3.6 billion years on Earth. Those rocks are present on the surface of Mars, and they will tell us a lot both about the way rocky planets evolve and also about things like habitable environments, and for me, linking this to the life question, I think the really exciting thing is, we will potentially be looking at an environment that was capable of having life originate, and that's of course one of the great questions. It's a great scientific question that is extremely difficult to treat as a science question because there's no evidence, no substantial evidence to compare it against. By going to Mars, we may actually be able to find environments like that and learn something really profound about the way life works.

Chairman BABIN. Thank you very much.

And Dr. Pappalardo?

Dr. PAPPALARDO. For Europa, we want to understand, is this really a habitable environment, Europa's ocean, lakes within the ice shell, and we think we know how Europa works but planetary scientists are always surprised when we actually go there with new instruments to test hypotheses. So we're going to both test hypotheses and explore and expect to be surprised. What I would love to see is some sort of oasis, that is, a place where there's liquid water near the surface, there's evidence of heat coming out, there are organics at the surface somewhere where we'd want to follow up with future exploration.

Chairman BABIN. Fascinating. Thank you. My time is up so I'd now like to recognize the gentleman from California, Dr. Bera.

Mr. BERA. Thank you, Mr. Chairman.

Dr. Elkins-Tanton—and I think each of you in your opening statements alluded to the fact that exploration is part of our DNA, you know, this natural curiosity, this desire for discovery, and the universe is, you know, unlimited in its possibilities of what we can learn. That brings us back down to Congress where we have to operate in the confines of limits. Each of you has talked about the Decadal Survey and alluded to a bit of the roadmap for some of our bigger missions and laying out some of the parameters for some of the medium-size missions.

Dr. Elkins-Tanton, as you talked about the Psyche mission and alluded to the importance of, you know, some of our smaller missions, how those—you know, what we discover, you know, they're able to be launched at a lower cost, et cetera. You know, there's some worry in that limited environment of Congress that we potentially focus on the big missions at the expense of the smaller missions, and we've got to found the right balance. Maybe if you want to expand on your comments and the importance of some of the smaller missions.

Dr. ELKINS-TANTON. Thank you very much. Indeed, I think this is well recognized at NASA, and I've heard Jim Green talk about a cadence, a process for deep exploration in space that you might fly by, you might orbit, you might land, and then you might rove, and indeed, you wouldn't spend all the money that you would have to spend to do a flagship mission on a body that we know little about, and so the smaller missions form a framework and they set the stage for the kinds of bigger expeditions that we want to do, and as my colleagues here have mentioned, every time we do something in space, it surprises us, and so we must try these smaller missions to find out where the biggest surprises are and then put our money on making the big, big discoveries.

Mr. BERA. Dr. Green, do you want to expand on the importance of the smaller missions?

Dr. GREEN. Indeed, the smaller missions are really our pioneers. They do go out and do some initial exploration. You know, smaller missions in the discovery framework is really the heart of that exploration process. You know, I mentioned several of them in my testimony like Dawn. Others that have come and gone while I've been at NASA headquarters include Messenger, another wonderful mission. Grail went to the moon, Messenger went to Mercury, and Grail studied the moon in new and unique ways.

And so indeed, the discovery line is really quite important for us, and then the next line is new frontiers. This is where we can now concentrate on the next level of detail. So important for us to make decisions on what our next flagships will be.

Mr. BERA. Great. Switching now to Mars and, you know, our telecommunications infrastructure and Mars, my understanding right now is that the Mars Reconnaissance Orbiter handles the majority of our telecommunications relay for Curiosity Rover, but the MRO was launched 12 years ago. As we look at Mars Rover 2020, you know, I guess, Dr. Green or Dr. Farley, would you like to kind of comment on, you know, will we still be relying on the MRO to relay that information back or are we thinking about, you know, what next steps for telecommunications?

Dr. GREEN. Well, telecommunications for any surface assets indeed go through our orbiters, and right now we have a wonderful network including MRO is Mars Odyssey, and also with partnership from ESA, other missions that are also orbiting Mars have that telecommunication capability. So in addition to those two, we also have with ESA the Mars Express mission and now the newly inserted into orbit, the Trace Gas Orbiter from ESA. Now, we also have Maven, which is not prime telecommunication capability but may become more dependent on using Maven as our aging assets occur. So indeed, supporting telecommunications is a real critical element of allowing us to now when Mars 2020 gets down on the ground be able to relay that data back so we take careful operations of all those missions and partner with other agencies.

Mr. BERA. Great. Dr. Farley, do you want to expand or——

Dr. FARLEY. I'll just say Mars 2020 has a very large demand to downlink data. We have a huge number of cameras. It's quite extraordinary. There's more than 20 cameras on the rover. And we will need downlink. As you point out, MRO is an aging asset but as Dr. Green pointed out, there are contingency plans to get us the data volume we need.

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

Chairman BABIN. You bet. Thank you. Good questions.

I now recognize the gentleman from California, Mr. Rohrabacher.

Mr. ROHRABACHER. Thank you very much, Mr. Chairman. It was noted earlier that one of the purposes of, or one of the benefits, I should say, of your activities is that you have these robots all over the universe and beyond that you are inspiring people with our capabilities.

And Mr. Chairman, let me just note that I've been around for a while, and I think that when we were deciding about the shuttle and we were deciding about Space Station, a lot of times the discussion was only on the immediate scientific payback, but I believe those two space projects have inspired generations of Americans now, and who knows how much more productive our people are, how much more visionary they are because of these investments in the shuttle and the space station, which were very expensive projects, I might add.

And back to expensive projects, let me just note that one thing that I find—one of our witnesses mentioned that the Decadal Survey was supposed to prioritize and it just seems to me standing back and listening to everything that we haven't had that prioritization and maybe we should—there's been—when you have so many projects at one time, it indicates that there hasn't been a real finding out of what priorities we need, and I'm certainly not an expert enough to tell you what those priorities should be.

Let me ask some specific concepts or ideas about the engineering that I don't know about. What type—well, first of all, is there any one of these missions that plan to—we know we've landed the robots on Mars. Do we plan to actually bring some material from Mars back to Earth before we plan to send human beings there and bring them back?

Dr. GREEN. Indeed, the Mars 2020 mission, which is going to core rock, providing a detailed look at the past Mars, the geological records in that rock, we are currently looking at a variety of architectures, and——

Mr. ROHRABACHER. Right, but we are going to bring them back?

Dr. GREEN. Our intention would be indeed that as the importance of these samples are noted based on the analysis that we do in situ that indeed we would plan on bringing samples back from Mars.

Mr. ROHRABACHER. Okay. The reason I ask that is, it seems to me that rather silly to think that if we can't bring back rocks that we're going to bring back people, and certainly if we aren't comfortable with the idea that we can bring back rocks, we should be focusing on getting that done before we talk about bringing people back.

The exploration, to me, that's the most inspiring. I just have to tell you that when we talk about going out and visiting those places where nobody has been, what type of fuel are we using? There was a mention about one of the things when we run out of fuel, it's going to land into Europa or something like that. What type of fuel is now being used in these various projects? We know you have to have a big rocket to get them going, but if they're going to keep going into the universe, what fuel do they use?

Dr. FARLEY. Yeah, Mars 2020 while it's on the surface will use a short-lived plutonium isotope so it's a nuclear power source.

Mr. ROHRABACHER. Any other——

Dr. ELKINS-TANTON. May I add to that? During cruise and while orbiting Psyche, our spacecraft will use solar electric propulsion, and this to me is so—it's in our heart at space age. You see the little blue plumes of the ions being shot out the back and it's all run by solar power, and in fact, this is another good proof of this technology which is eventually going to be critical for getting people to Mars.

Mr. ROHRABACHER. Yeah, I remember the solar sail project, which also was very exciting. These new concepts that—and you—and let me just note, Mr. Chairman, the fact that we can actually provide a fuel for something that far away indicates that maybe we have some knowledge that's going to really help us here.

But one last thought. I would hope that—again, I think the Moon is close by and whatever we can actually get a benefit of going back there, we should before you take the next step. However, the most important thing was, if Mars—can I ask permission for one minute for this question? And that is, you have indicated that Mars was totally different thousands of years ago. Is it possible that there was a civilization on Mars thousands of years ago?

Dr. FARLEY. So the evidence is that Mars was different billions of years ago, not thousands of years ago.

Mr. ROHRABACHER. Well, yes.

Dr. FARLEY. And there would be—there's no evidence that I'm aware of that——

Mr. ROHRABACHER. Would you rule that out? See, there's some people—well, anyway——

Dr. FARLEY. I would say that is extremely unlikely.

Mr. ROHRABACHER. Okay. Well, thank you all, and thanks for the good job you're doing. God bless.

Chairman BABIN. Thank you, Mr. Rohrabacher. I'm looking forward to finding out what's up there, that's for sure. And just last month, we had a great hearing in here on in-space propulsion, which was super, super interesting.

Okay. Now I recognize the gentleman from Colorado, Mr. Ed Perlmutter.

Mr. PERLMUTTER. Thanks, Dr. Babin.

And good morning, and thank you for your testimony today, and a truism in life is, everything's relative, and when we're talking about small, medium and flagship projects that you all are undertaking, you know, to Mrs. McGillicuty from Lakewood, Colorado, they're all major undertakings, and Dr. McKinnon and Dr. Elkins-Tanton, I mean, we're here for I dipped into the future far as human eyes could see, saw the vision of the world and all the wonder that would be. And all of you are working on kind of the ultimate question of humanity, why are we here and what else is out there. And so I just appreciate your willingness to take on kind of the nuts and bolts for us to start knowing the unknown, and this Committee is so exciting to all of us here and to hear the work you're doing, we appreciate it.

Now, I'd like to start with Dr. Farley. One of the things that I am focused on is trying to get our astronauts to Mars by—you guessed it—2033, all right, and so first question I have is for you. How will this rover, you know, 2020, our mission in 2020, how will that help us, inform us to get humans to Mars by 2033?

Dr. FARLEY. Well, I think it's important to note that Mars 2020 has a very strong collaborative involvement from the human side of NASA, and that is manifested in several different ways. Most notably, you heard about the MOXIE demonstration of in situ resource utilization. In addition, we have a weather station, which will characterize the environment, will also characterize dust, and dust on Mars is a big concern for human explorers, and in addition, during entry, descent and landing, we'll have a very sophisticated observation package. Understanding what goes on during EDL is absolutely critical and almost impossible to simulate either on a computer or in an analog experiment on Earth, so this is very important data, and as Dr. Green mentioned in answer to the question of, you know, bringing rocks back before people back, it's a very sensible thing to do. Obviously there's no commitment to do that but there will be a tempting target to learn from when those samples come back.

Mr. PERLMUTTER. Dr. Elkins-Tanton, where the heck is Psyche, I mean other than up here or wherever it might be?

Dr. ELKINS-TANTON. Psyche is in the outer main asteroid belt between Mars and Jupiter. It's about three times farther from the sun than the Earth is.

Mr. PERLMUTTER. Okay. Dr. Pappalardo, my question to you, you know, often I talk about Star Trek or Star Wars or Men in Black but what you're doing reminds me of 2001: A Space Odyssey and, you know, our mission at that point to get to Jupiter. So explain to me in this investigation, study of Europa, what are the—I mean, what do you really—what do you see already and what do you expect to see from this mission?

Dr. PAPPALARDO. Let me preface by saying I'm a big Trekkie. And our Europa science team of about 130 people we have as our mascot, our totem, a giant monolith that we tote around our meetings.

So we have tantalizing hints from the Galileo mission about what Europa is like. At high resolution we have precious little data. We have one six-meter-per-pixel image. We have ten-meter-per-pixel images that you can count on your hands and toes to get an idea of what Europa is like, and so this creates this picture of what we think it's like, an ice shell probably about 20 kilometers thick above a saltwater ocean and then the rocky mantle below. But, you know, right now it's kind of a uniform picture whereas any world you explore in more detail and then you find out how it varies from place to place. We've seen this happen with our understanding of Mars where we first thought it was a cratered ball because we saw the cratered part of it and then we started understanding more and more, and now it's at the outcrop scale we see differences. So we're going to understand how Europa works as a world. We're kind of in our level of understanding that we were before plate tectonics on Earth where we don't really get how all the little pieces we see at the global scale fit together and we're going to find more little pieces as we explore with Europa Clipper.

Mr. PERLMUTTER. Thank you——

Dr. MCKINNON. If I could——

Mr. PERLMUTTER. —Mr. Chair, and I yield back.

Dr. MCKINNON. I'll just pipe in just for a second.

Mr. PERLMUTTER. Oh, I'm sorry.

Dr. MCKINNON. We're—you know, we have tantalizing evidence from the Hubble space telescope that Europa's venting material into space, and we hope when we get there we'll be able to confirm that and literally fly through it and sample it and analyze it.

Mr. PERLMUTTER. Thank you, Doctor.

Chairman BABIN. Thank you. Good questions and great answers. I now recognize the gentleman from Oklahoma, Mr. Lucas.

Mr. LUCAS. Thank you, Mr. Chairman, and I share my colleagues' enthusiasm up here and clearly the enthusiasm of the panel.

Let's visit mechanically for a moment, Dr. Farley, about the nature of the rover programs. A lot of citizens back home are very sensitive about how we spend their money. Could you take me through a discussion about Mars Rover 2020, the advances and the technology and the science gathering used in that compared, say, to Curiosity as I explain to my constituents back home why it's important we do this?

Dr. FARLEY. Okay. Well, in reference to Curiosity, the reason this mission can be done in a cost-constrained way is to take advantage of the platform that the Mars Science Laboratory developed. It should not be underestimated how difficult any new undertaking in space is. So we start off with that, and this allows us to actually focus on the stuff that is new, and there are new science instruments that will make new kinds of observations, and I think those—they will be directed towards characterizing samples that will form the basis of a discussion as to whether those samples should be brought back, and if those samples are brought back, I think they will revolutionize our understanding of many different things.

If you look at the history of our understanding of many aspects of the solar system, it was completely changed by the return of the lunar samples, and that of course is an abiological world. My expectation is, if samples come back from Mars, this will be a revolution that goes way beyond sort of planetary science and geology. It will actually extend into asking and looking at samples for the first time to address questions about what life not as we know might look like, and I'll just put it out there as a profound question for which we don't have an answer, how does one look for life as we don't know it? And we may have samples in our collection in 20-some years where we will need to answer that question. I think the public will be fascinated by that question.

Mr. LUCAS. Dr. Pappalardo, discussing the plumes just a moment ago, tell us mechanically about what it will be involved in being able to use the Clipper in a way to verify their existence, whether it's navigating the flybys or the sensors on board. Expand for just a moment on that if you would.

Dr. PAPPALARDO. Well, first, there're continuing observation with the Hubble Space Telescope so we hope, expect to have new data before we arrive so we can understand if they're real, if they're periodic in some way. But say we don't or say they're sporadic and we need to understand them better. We would use the time—we have a big looping first orbit. We would use that time to monitor and try to understand whether there is evidence of plumes, both from imaging and from ultraviolet observations where we could see the glow from such plumes. And then during the mission, we're planning on monitoring the whole time when we're a little farther from Europa to look for plumes. And then if there are plumes, then we will certainly want to target them. Whether it be in the primary mission or the extended mission, we'll figure that out, but we'll want to fly through as low as possible, meaning about 25 kilometers, 16 miles off the deck if we can, depending on the location, depending on whether we can or not, and for that matter, how much particulates because you can damage—you can risk the spacecraft, and by flying through, we'd be able to sample that stuff directly and get a direct sampling of what's in the interior of Europa. We don't know for sure. Assuming the plumes are real, we don't know for sure if they're coming from the ocean or from lakes within the ice shell, and we would analyze the gas and the dust that's coming off to say a lot about what the interior composition of Europa is like.

This is analogous to what Cassini has done at Enceladus at Saturn, which does have plumes that spew into space.

Mr. LUCAS. So an incredible amount of prep, an incredible amount of skill in maneuvering the mission, and just a little bit of luck would be a good thing too.

Dr. PAPPALARDO. And we have a group of scientists. We're thinking that through as we meet and discuss the possibilities and working with the engineers to do so.

Mr. LUCAS. Absolutely. Thank you, Doctor.

Yield back, Mr. Chairman.

Chairman BABIN. Thank you.

I now recognize the gentleman from Virginia, Mr. Beyer.

Mr. BEYER. Dr. Babin, thank you very much, and thanks to all of you for being here.

Dr. Farley, a relative softball question, but in your testimony, you say that past life Mars 2020 seek evidence of past life in a fossil-like Earth-like environment that existed in the first billion years after the dawn of the solar system—some of the most profound scientific questions of our time. Why are they profound?

Dr. FARLEY. Well, the two questions that I was alluding to there are the, is there life beyond Earth, and I will just make the general observation from my interaction in the science community, the discovery of thousands of extrasolar planets has converted this question from something where most scientists that I knew would say it doesn't seem that likely to wow, it seems really unlikely that we are alone. The only way I think you could really put some scientific evidence to that is, if you look in a habitable place, is it inhabited? There may be lots and lots of habitable places out there, and that goes to the question of the spark that makes life happen, and so that I think is a really profound question that we will go after. Is life out there? Was it out there? And what is necessary—what are the environments like where life might evolve, and those are really profound questions.

Mr. BEYER. Thank you very much.

Moving from life to metal, Dr. Elkins-Tanton, a couple of quick questions. How do we know that it's metal? Is it a spectrometer or whatever? How do you know it's the only one in the solar system?

Why did you name it Psyche? And do you really think it used to be a planet and the rock and the like was stripped off of it, that it was like Earth or Mars or Venus?

Dr. ELKINS-TANTON. Right. Okay. Let's see if I can remember this and get it all in your time. So the first question is how do we know it's metal. We've never seen Psyche visually as more than a dot of light but we get radar returns from Arecibo, which seems to me to be also just a technological miracle. We can actually send radar from Arecibo, get the returns, see that the radar has interacted with the material of Psyche in a way that it only interacts with metal, so that's a really key one. We can also see its reflected spectra consistent with metal and its density consistent with metal but the radar returns are the key. So we're pretty certain it's metal. There are other smaller metal asteroids like Cleopatra, which is shaped like a dog bone. If you haven't seen it, you should google it. It's a great one. But they're all much smaller. They seem to be the shrapnel of leftover from planetary collisions. All the really heavy, rocky, metallic material is either in the inner solar system or in the asteroid belt or hidden inside ices and gases in the outer solar system. So we're pretty sure that what we see in the asteroid belt is it for metal and Psyche's the only big round one.

Now, Psyche was discovered in, I believe, 1852 maybe—I might have the date wrong—by an astronomer in Naples, and he named it Psyche. It was the 16th body found in the asteroid belt by a group of astronomers called the Celestial Police who were trying to set right to the solar system and find the planet that was there, and they didn't, and they were naming them all after gods and goddesses, and so Psyche's number came and there it is, Psyche.

There was one more question. What was it?

Mr. BEYER. Did it used to be a planet?

Dr. ELKINS-TANTON. Oh, we're pretty sure it was but, you know, true to my scientific training, everywhere I've been in the world and given talks on Psyche, I've asked scientists what else could it possibly be. If it's not the core of a planet, how do we make this? And our best other guess is that it could be material that had all the oxygen stripped off it by heat very close to the young sun. Theoretically, people think that kind of material could exist but we've never found an example of it, and so if it's not a core, that would actually be more exciting. It would be something we've never seen before.

Mr. BEYER. Exciting either way.

Dr. ELKINS-TANTON. Thank you. I think so.

Mr. BEYER. And I want to point out that Jules Verne did think we could do a journey to the center of that Earth.

Dr. ELKINS-TANTON. I visited that Icelandic volcano. It didn't work for me.

Mr. BEYER. Dr. Green, you talked about looking for evidence of organic materials on Ceres and that Bennu—I hope I pronounced it right—is believed to contain water and organic compounds such as amino acids. Have we gone beyond amino acids to proteins to nucleic acids? Are we going to leap to DNA and RNA?

Dr. GREEN. Well, of course, we would call that an ever-increasing knowledge about potentially the right stuff that life either is made of or produces as a byproduct. That's all part of what would be a ladder of life but the only way we can definitively determine what's really at Bennu is to bring samples back, and that indeed is planned. When we get into orbit around Bennu, as we start getting August of next year, we'll be studying it for about 500 or so days picking the right location, going down, sucking up material, perhaps as much as a kilogram, and then bringing that material back, and that's when we'll do the detailed look at what's in it. It'd be great to find more complex amino acids and other organics.

Chairman BABIN. Thank you, Mr. Beyer.

I now recognize the gentleman from Florida, Dr. Dunn.

Mr. DUNN. Thank you very much, Mr. Chairman. I think the Space Subcommittee always seems to be most inherently optimistic committee of the House, and you know, the can-do attitude of our panelists is absolutely infectious. I can only hope that you'll expose yourselves to the Senate sometime soon.

I want to frame my questions to the panel with this thought. The proof of life that is truly extraterrestrial life is an event that is on the level with the first Moon landing, so long after posterity's forgotten all of the proceedings of this Committee and relegated the history of our planetary explorations to the dusty bookshelves, everyone will remember the event that proved extraterrestrial life.

So with that thought, Dr. Farley, let's say everything works out perfectly on the Mars 2020 lander. You obtain appropriate terrestrial samples. What would you consider to be the elements of a biosignature, you know, a biotic chemistry, if you will?

Dr. FARLEY. So I'll give two different answers to that. One is, what can we detect with the rover and what could we defect if we bring samples back, and with the rover, we have the capability to make a map at the scale of about a postage stamp of the distribution of organic matter. That's one of our key observational capabilities, to take a rock and make a map of organic matter, and on that same postage stamp-size piece of material, we can also map the elemental composition. And when one looks at ancient terrestrial rocks, this co-registration of organic matter and elemental composition is the key to identifying on a planet where you already know there's life to identify the most ancient life on Earth. So we will make those kinds of observations, but just like with the terrestrial case, those kinds of observation are seldom definitive. They're the kind of thing people argue about for decades, and if we bring samples back, they're a far greater diversity of observations we can make. Dr. Green was talking about different—making observations of the ladder of life, looking for more and more complex organic molecules whose composition is only reasonably associated with life as opposed to abiological processes.

Mr. DUNN. I guess I kind of thought the problem with bringing it back is everybody always wonders about contamination, you know, did you sterilize the ship so thoroughly on the way out and the way back that you can be certain that this came from Mars. So if you do a test as they did on the Viking, they are in in situ on Mars, and if you could design a better test, a better chemical test, what would that be and would it involve, as you and I spoke before the meeting, stereoisomers and——

Dr. FARLEY. So one of the complications of looking for ancient life is that there will be degradation of organic molecules.

Mr. DUNN. You're looking for ancient life. I'm looking for life today.

Dr. FARLEY. Right. We have no capability on the rover to look for extant life at the microbial scale. We can't tell the difference between live and dead, but if those samples came back, as I mentioned before, I think there will be a lot of interest in actually developing technologies, and they would include things like stereochemistry and that sort of thing.

Mr. DUNN. So would you elaborate? Because I'm not sure everybody on the Committee is thinking about stereochemistry. What's the significance of discovering an ongoing biochemical or chemical process, a biotic process that has, you know, solely left- or right-handed metabolite?

Dr. FARLEY. Sure. So one of the key ways that one identifies molecules that are involved in life is that all life has a preference for a particular handedness of one of the organic molecules. There's two different confirmations that these organic molecules could be in and most abiological processes produce them in equal abundance whereas life because it has a machinery involved, very specific machinery, tends to produce a specific chirality, a specific confirmation of these organic molecules. So this is really a critical observation for establishing that life is involved. There are very, very few abiological processes that would produce stereochemically specific molecules.

Mr. DUNN. So production of a stereospecific metabolite would be a pretty strong presumptive proof of life, extant life, on Mars if you ran it the way the Vikings rover ran that? What the Viking rover did is run that test without stereoisomers.

Dr. FARLEY. Right.

Mr. DUNN. So if you ran the same test and checked for stereoisomers by having left- or right-handed substrates——

Dr. FARLEY. Yes, that would be a very important test, and I'm aware that there are instruments under development for actually making those kind of measurements in space.

Mr. DUNN. I agree there are. I'm out of time. I would say that that's about a 2-kilogram package. I look forward to talking to you outside of the Committee structure, and I yield back.

Chairman BABIN. Thank you. You remember a lot from your training, Dr. Dunn.

Let's see. Another gentleman from Florida, Mr. Posey.

Mr. POSEY. Thank you, Mr. Chairman.

Dr. Green, traditionally, planetary exploration was a public sector endeavor that taxpayers took care of. Today the U.S. private sector companies are beginning to invest and develop planetary exploration programs. What is NASA doing to facilitate and encourage private sector investment and participation in planetary exploration?

Dr. GREEN. I believe there's a whole range of things that we've been involved in. If you take an example of the concept of going to asteroids and being able to extract certain metals and other compounds of interest, the first thing that they're going to need to know is, where are they, what is their characteristics, how to get to them, and indeed, we are doing an extensive finding project where we'll find our small bodies, we'll catalog and characterize them, and all that information will be critical, and we've discussed that openly in many different meetings working with that sector.

Another sector is a series of commercial opportunities going to the moon. Now, this could be a really important element for scientists to be able to work with the commercial entities and be able to obtain rides to be able to bring back material or examine certain regions on the moon that are extremely important. The moon is still quite valuable in terms of being able to provide us an enormous amount of science that be done. It's been a witness plate of over 4 billion years of impacts and can tell us a lot about what's happened to our environment and what's happened to the Earth. So those partnerships are beginning. There are some that are done through a Space Act agreement and others are done through collaborations and discussions at a variety of venues.

Mr. POSEY. Thank you very much. That's a good answer.

Given the important role of robotic planetary missions in advancing human exploration capabilities, how can the current and future planetary missions be integrated into the human exploration roadmap, which we've asked NASA to produce?

Dr. GREEN. Well, of course, from my perspective, planetary scientists are really the guides. You know, they're really the ones that go out first. Human exploration is not Star Trek. It's not "go where no human has gone before." In our program, and NASA is really all about sending humans to locations beyond low-Earth orbit out into the solar system, be able to live, work, but also return, and all those require not only where you're going but the characteristics so how to get there, what are the kind of science and other activities one can do on station, and then of course the challenges of entry, descent and landing for any of the bodies they choose to go to.

We pioneer a lot of that, you know, in terms of being able to look at those environments, collect that information, but also pioneer some of the initial technologies that allow us to get our rovers and other machinery at various locations, whether it's the moon or Mars.

Mr. POSEY. Can you describe the infrastructure that missions will be putting in place around Mars and Europa to support future missions? For example, will NASA be able to use the Europa Clipper to support future Europa missions, namely the lander?

Dr. GREEN. Yeah, actually as Lindy mentioned earlier, in planetary science, we really have a very important paradigm that we follow. It's flyby, orbit, land, rove, but also return those samples. And indeed, the Europa Clipper gives us that opportunity to do a detailed examination of Europa that provides high-resolution imaging that gets us right to where we want to go that makes the next mission, which would be notionally a lander, to be able to land safely and perform the science that we wanted to do. So indeed, each of these missions are very much related and depend on the success of the previous mission.

Mr. POSEY. Thank you very much. I yield back, Mr. Chairman.

Chairman BABIN. Yes, sir. Thank you, Mr. Posey.

And another gentleman from Florida, Mr. Webster.

Mr. WEBSTER. Thank you, Mr. Chairman.

Dr. Green, is there any interest in going to the outer planets to do the same level of investigation and so forth, or is that just too expensive and too far?

Dr. GREEN. Well, indeed, when one looks at the science that's been delineated by the community and the National Academies' Planetary Decadal, we have an extensive desire to be able to go out to the outer reaches of our solar system where our planets like Neptune and Uranus reside. Neptune and Uranus, although they are big what look like giant planets like Saturn and Jupiter, they actually are very different in many ways. They have a whole series of different compositions associated with them. We call them the ice giants. You know, they're not completely hydrogen and helium. They have ammonias and a whole series of other elements that they have obtained in that accretion process that we know very little about and so being able to go out to Uranus and Neptune are extremely important.

We just completed a major study and have worked with the scientific community to determine what are the characteristics of the measurements we want to make in those regions but also how do we be able—how are we able to get out there perhaps in the second half of the next decade and really get into orbit and analyze that environment.

Mr. WEBSTER. Is that desire which you spoke of funded?

Dr. GREEN. Right now that's only at the study level. The Planetary Decadal is quite clear that the top things that we should be doing we are doing but, you know, you have to prepare, you have to spend some time on your future or you don't have that future, and so while we do this planning, while we do this mission concepts and studies, those are indeed laying the groundwork for our future work.

Mr. WEBSTER. Is Voyager still broadcasting?

Dr. GREEN. Yes. Both Voyagers are still broadcasting. Now, they're very far away. They're more than 120 astronomical units away where one astronomical unit is the distance between the Sun and the Earth, so they're very far out there, and therefore—and they have little power left although it's a radioisotope power. It's a long-lasting power system. They're sending back a handful of bits whenever we can turn our big telescopes and bring that data back but they're doing a marvelous job, really exploring that outer reaches of the heliosphere we call it.

Mr. WEBSTER. What's their wattage?

Dr. GREEN. I would only guess but I would believe it's on the order of tens of watts. That's all that's left.

Mr. WEBSTER. And then what would be the final date that it won't be able to broadcast anymore? You're saying it's diminishing now, right? Is that what you said?

Dr. GREEN. Yeah, it uses—utilizes radioisotope, plutonium 238, which decays over time, and how that works is, you bring a mass of plutonium together, it's radioactive. You shield that and that radioactive capability where the nucleus of the atom blows apart heats and that heats a sleeve that's around this material and then that heat through a thermal couple is used to charge a battery and then you run your experiments off of it. And so over time as the radioisotope decays, then there's little heat involved, and now you have major power management activities that you have to do, which they're doing to really keep the spacecraft going because not only is it providing power but it's also providing warmth for the instruments and the spacecraft subsystems.

I can't give you, although I'll take for the record and get back to you on exactly what our prediction is when it will really have not enough power to sustain itself or it'll be at a distance far enough away that we will not be able to track it.

Mr. WEBSTER. Thank you very much. Yield back.

Dr. MCKINNON. If I could add just one thing to do that, that the New Horizons spacecraft, which passed by Pluto and is on its way to another body in about a year and a half, will also leave the solar system and it's also powered by a similar radioisotope heating system and we anticipate that we'll be able to contact and operate the spacecraft into the 2030s.

Chairman BABIN. Thank you for those fascinating questions.

I want to ask one more question. Why do we think that Mars lost its atmosphere billions of years ago? And Mars is farther away from the sun than Earth, and I'm just going to—Dr. Farley, would you take a stab at that?

Dr. FARLEY. There may be others here that know more than I do about this but this is one of the central purposes of the Maven mission, to try to understand why the atmosphere was apparently lost, and one of the leading candidates is that the planet uses hydrogen, and—to space, and that causes—that hydrogen is produced by the breakdown of water, and so you break up the water molecule and the hydrogen escapes. You cannot re-form the water molecule so that's a way to desiccate it by interaction with the solar wind, and one of the jet reasons for that is that Mars apparently lost its magnetic field very early in its history whereas Earth did not so the magnetic field protects the Earth from the radiation from the sun that causes this to happen.

Chairman BABIN. Thank you. Anybody else?

Dr. ELKINS-TANTON. Yeah, I'd like to add to that. I've worked on that directly. And so this is part of our interest in Psyche as a core is to understand the magnetic field, but to add to what Ken has said, it's also possible—another hypothesis is that when Mars was very young and still hot, its atmosphere would have been inflated through heat to be further away and less well bound to the body itself, and the more active young sun could actually have stripped it at that time. And so we don't know exactly when it was stripped or the processes, and that's another thing we'd like to learn to find out how applicable it is to the Earth.

Chairman BABIN. Great. Those are fascinating answers. Thank you so much. I think I'm the only member left here.

But I want to say how much I appreciate all of you fascinating and well-educated scientists for being here, and we appreciable your valuable testimony. And also, the record will remain open for two weeks for additional comments if any Members would like to submit those.

So with that, this hearing is adjourned. Thank you.

[Whereupon, at 11:44 a.m., the Subcommittee was adjourned.]

Appendix I

ANSWERS TO POST-HEARING QUESTIONS

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Jim Green

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Planetary Flagship Missions: Mars Rover 2020 and Europa Clipper"

Dr. Jim Green, Planetary Science Division Director, Science Mission Directorate, National Aeronautics and Space Administration (NASA)

Question submitted by Ranking Member Ami Bera, House Committee on Science, Space, and Technology

1. With two planetary flagship missions currently in development, to what extent can the FY 2018 NASA budget request and current out-year projections support the addition of a Europa lander mission without jeopardizing the programmatic balance of the planetary science portfolio? What is the earliest date such a mission could reasonably be added without jeopardizing that balance?

   Answer: NASA's balanced Planetary Science portfolio, in accordance with guidance in the latest Planetary Science Decadal Survey, currently supports two large strategic missions in the five-year budget horizon (Mars 2020 and Europa Clipper); thus, the Europa Lander mission was not included in the FY 2018 President's budget request since it could not be accommodated without significant impacts to other programs, such as the Discovery or New Frontiers program lines. Additionally, a Europa lander was not recommended in the last planetary Decadal Survey conducted by the National Academies, which is currently undergoing its mid-term review.

   Beginning design and development work on a lander before the science community is able to evaluate data from the Europa Clipper mission may impact the science return from a future lander mission.

2. In light of discoveries made since the decadal survey was published and direction from Congress, NASA added Ocean Worlds to the list of mission themes for the fourth New Frontiers Announcement of Opportunity and is studying a lander mission to Europa. Under current fiscal constraints, does the NASA planetary science program have the flexibility it needs to respond to new discoveries in a way that maximizes the science return while also staying true to the science goals and priorities recommended by the decadal survey? How does and should NASA engage the science community the process of responding to new discoveries?

   Answer: As in the past, NASA will continue to rely on the science community to identify and prioritize leading-edge scientific questions and the observations required to answer them – primarily through the National Academies decadal survey process. Despite fiscal constraints, NASA is dedicated to being responsive to the top priorities within the current decadal survey, as evident through our Mars 2020 and Europa Clipper missions.

NASA is also committed to planning for a robust planetary science future. For example, NASA recently convened an ad hoc committee via the National Academies to review the response of NASA's Planetary Science program to the 2011 Decadal Survey. In addition to assessing the degree to which NASA's current planetary science program addresses the strategies and priorities outlined in the decadal, the committee will recommend any actions that could be taken to optimize the science value of the planetary science program, including how to take into account emergent discoveries since the decadal in the context of current and forecasted resources.

3. A *Science* Magazine article published in May revealed that, despite the fact that at least 25 percent of planetary scientists are women; women have made up just 15 percent of planetary mission science teams over the past 15 years. Can you give us some insight into what steps NASA is taking to increase the representation of women on its planetary science missions?

   Answer: NASA is committed to diverse representation within our missions and our Planetary Science Division (PSD) specifically has been working over the past few years on a multidimensional strategy to increase the representation of women. While PSD has various missions and teams that have women as Principal Investigators or deputies (four of the five Principal Investigators selected for Phase A studies in the last Discovery competition were women), we are also striving to ensure that participation by women scientists and engineers is growing in in leadership areas such as:
   - Discipline scientists, program executives and program officers
   - Planetary Science Advisory Council (PAC) membership
   - Review panels

   This strategy is based on the idea that when particular attention is paid to ensuring the infrastructure is diverse, it will not only provide opportunities for women in planetary science but also encourage young women scientists in finding role models to help position themselves on leadership paths. The strategy has already shown to be successful; for example, our current (and previous) PAC chairperson is a woman scientist. Along with our review panels, the PAC membership was and continues to have a solid female representation.

4. NASA has managed several large flagship missions in planetary science as well as in other NASA science divisions. How is that experience being leveraged for the Mars 2020 and Europa Clipper missions? Has NASA made any changes to the way it manages these two missions based on the experience gained and lessons learned from past flagship missions? If so, what are they?

   Answer: Lessons learned are an integral part of NASA missions and as an agency, we strive to implement new and innovative ways for our workforce to share their knowledge not only as part of flagship missions, but also as part of their normal everyday work. In particular, NASA's three major project management requirements documents specify the sharing of knowledge from lessons learned and direct project managers to develop a plan for collecting and sharing lessons learned.

For example, NASA completed a formal Mars Science Laboratory (MSL) Lessons Learned Study, which the Mars 2020 team is utilizing for guidance. Mars 2020 is also strategically using heritage technology based on the MSL Curiosity rover to help manage cost and risk for a new flagship mission.

Based upon our experience with previous flagship missions, NASA transitioned to a confidence-level budgeting approach for all of our external cost commitments. Each mission is required to be budgeted at a 70 percent cost confidence, which ensures that the aggregate portfolio of missions is highly likely to remain within the forecast costs. We have developed tools to develop confidence-level budgets, and performance data shows that the aggregate SMD portfolio remains under cost commitments for missions over the last 6 years. Mars 2020 and Europa Clipper are both following this process.

For the Europa Clipper Mission, two additional steps are being taken to ensure cost control: (1) Margin on obligations-to-go are being reported to HQ each month for each instrument, as instruments have historically had significant cost growth; and, (2) A new tool has been developed to map each instrument's capabilities onto the science requirements, allowing analysis of possible overlap between instruments and identification of the consequence on science objectives if an instrument must be reduced in capability. Both of these two approaches are new, and Europa Clipper will be the first mission to use them.

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Planetary Flagship Missions: Mars Rover 2020 and Europa Clipper"

Dr. Jim Green, Planetary Science Division Director, Science Mission Directorate, National Aeronautics and Space Administration (NASA)

Question submitted by Rep. Bill Foster, House Committee on Science, Space, and Technology

1. The Apollo lunar landing program cost $24 billion in 1960s dollars over 10 years. That means NASA set aside 4 percent of U.S. GDP to do Apollo. Today, 50 years later, NASA's budget is about $19 billion per year which is less than one half of one percent of GDP.

   If we are serious about this Mission to Mars, we need to get serious about producing a realistic cost estimate. Do you have what you believe is a realistic upper and lower limit to the cost for getting to Mars? If so, please share that estimate with this subcommittee.

   Answer: The NASA Transition Authorization Act calls on NASA "to enable humans to explore Mars and other destinations by defining a series of sustainable steps and conducting mission planning, research and technology development on a timetable that is technically and fiscally possible". In keeping with this direction, NASA has formulated a set of principles for sustainable exploration that begin with fiscal realism and include a gradual buildup of capabilities over time and the infusion of new technologies as they mature.

   NASA's strategy is designed to embrace infusion of new technologies and new commercial and international partnerships from the present day through the accomplishment of human presence on Mars. Because the timing and impact of these are not quantifiable in advance, establishing a cost estimate for the whole endeavor is impractical.

   NASA's overall exploration goals and objectives, strategy, hardware and missions, and key decision timeframes will be articulated by the Human Exploration Roadmap due to the Congress on December 1 of this year. As NASA learns from initial missions using SLS and Orion, and the development of deep space habitation and in-space propulsion, the Agency will formulate cost and schedule details of future goals and hardware, and this analysis will be reflected in future budget requests so the Congress will annually be updated on projected accomplishments and resource requirements for the next five years.

Responses by Dr. Kenneth Farley

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Planetary Flagship Missions: Mars Rover 2020 and Europa Clipper"

Dr. Kenneth Farley, Mars Rover 2020 Project Scientist; Professor of Geochemistry, California Institute of Technology

Question submitted by Ranking Member Ami Bera, House Committee on Science, Space, and Technology

1. What is the status of the mission-critical Mars 2020 Sample Caching System?

Answer: The Mars 2020 Sample Caching System (SCS) successfully completed it's Critical Design Review (CDR) in January 2017. A number of key Engineering Development Units (EDUs) have been delivered into subsystem integration and test, including the rotary percussive coring drill which was delivered in March. The team is now primarily focused on fabricating components for the flight models and flight-like engineering and qualification models. Assembly work has begun on this hardware and will run through the summer of 2018. Notably, critical actuators required in the sampling system mechanisms (robot arm, sample handling arm, coring drill, etc...) have been progressing well at subcontractors and are expected to support the sampling hardware build schedules. Contamination control budgets, which monitor SCS compliance to the aggressive Level 1 biological and organic cleanliness requirements, continue to show good margins. SCS flight hardware schedules, with schedule margin, show all hardware deliveries complete by the end of calendar 2018. The Project maintains additional schedule slack between this date and the flight hardware need date of May/June 2019. The SCS subsystem is challenging and will remain the critical path for the project through 2019. However the project has to-date successfully addressed technical and implementation issues without impacting planned delivery dates.

Responses by Dr. Robert Pappalardo

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Planetary Flagship Missions: Mars Rover 2020 and Europa Clipper"

Dr. Robert Pappalardo, Europa Clipper Project Scientist, Jet Propulsion Laboratory, California Institute of Technology

Question submitted by Ranking Member Ami Bera, House Committee on Science, Space, and Technology

1. The 2017 Consolidated Appropriations Act directs NASA to launch the Europa Clipper aboard an SLS launch vehicle. However, NASA has reported to the Committee that SLS will not have its first test flight until no earlier than Fall 2019. When does the Europa Clipper project need to select a launch vehicle? What is the impact of launch vehicle uncertainty on the Europa Clipper project's ability to proceed through development within its preliminary cost and schedule estimates?

   Answer: NASA plans to baseline the Europa Clipper mission in FY 2018 and the selection of the launch vehicle is targeted for no later than the project Critical Design Review in late 2019, but potentially sooner. Preliminary cost and schedule estimates incorporate launch vehicle uncertainty so there is minimal to no impact on the project's ability to proceed through development within the identified ranges

Responses by Dr. Linda T. Elkins-Tanton

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Planetary Flagship Missions: Mars Rover 2020 and Europa Clipper"

Dr. Linda T. Elkins-Tanton, Director and Foundation Professor, School of Earth and Space Exploration, Arizona State University; Principal Investigator, NASA Psyche Mission

Question submitted by Ranking Member Ami Bera, House Committee on Science, Space, and Technology

1. What are your responsibilities as Principal Investigator on Psyche? In your prepared statement, you note the challenge of transitioning from a traditional academic position to organizing, inspiring, and leading an interdisciplinary team. What, if anything, would help to better prepare researchers to assume roles as PIs and mission leaders?

   Answer: In overview, the mission Principal Investigator for the Psyche mission is responsible for overall mission success, and for the scientific integrity and execution of the mission within committed cost and schedule. The Principal Investigator oversees the team organization, arbitrates science priorities and progress, and oversees the delivery of mission data sets to the Planetary Data System. The Principal Investigator is the ultimate decisional authority on the Psyche team. The Principal Investigator is responsible for ensuring that all mission participants are able to exercise the rights and execute the responsibilities laid out by their role's definition or by the Team Guidelines.

   Early in mission formulation I was responsible for putting together the team and deciding, in concert with Jet Propulsion Laboratory leadership, on the strategy for mission, including science goals and how the mission fits with NASA priorities. Throughout this process I have called upon knowledge I gained while working as a management consultant and in running small businesses before I returned to academia for my PhD. I remain convinced that team culture is among the most important attributes for project success.

   In traditional academia, by contrast, success is often gained by being willing to refute others, to compete both within and outside of one's institutional colleagues, and accrue credit and attention to oneself.

   These skills can be antithetical to a high-functioning team, where shared credit and successes of others need to be highly valued, and where misconceptions and errors need to be rapidly shared and never punished.

Many times I have been told that organizational skills are "soft" and that they can be done by any intelligent person – that is, they are not a learned skill, or not substantial enough to deserve learning. This kind of misunderstanding is not ubiquitous in science in first-rank universities but it surely does exist.

At both the Carnegie Institution for Science (my previous employer) and at Arizona State University I have experimented continually with workshops to train these critical leadership skills. Here are some thoughts that may be more broadly useful:

- We see students losing presentation and communication skills (other than the strictest and most traditional conference skills in our fields) as they progress from undergraduate to graduate training. For example, graduate students are seemingly less willing and able to speak for the lay audience after they have proceeded past the first or second year of their Ph.D., since they are training so intensively to use the language of their field. Thus intervention needs to occur at all levels.
- Both junior and senior scientists benefit from training in leadership, mentorship, management, team-building, negotiation, budgeting.
- Training in these topics can help lessen the loss of underrepresented groups at the postdoctoral stage.
- Academic scientists and engineers can be turned off by even highly talented business consultants, because we are trained so rigorously to avoid anything that smacks overtly of marketing or self-promotion. Thus, choosing and preparing the instructor is critical for success.
- A culture of valuing and rewarding leadership skills can be created in the university and supported by NASA and other governmental agencies. We are initiating online training through the Psyche mission, and I would welcome collaboration on this topic.

2. A *Science* Magazine article published in May revealed that, despite the fact that at least 25 percent of planetary scientists are women; women have made up just 15 percent of planetary mission science teams over the past 15 years. What are your thoughts on the underrepresentation of women on planetary mission teams? What more can NASA do to improve the representation of women on planetary science mission teams?

Answer: A useful starting point is an examination of how mission teams are selected. Leadership within the NASA management center generally chooses, or at least suggests, the key management for the mission on the engineering side, and the lead scientists (either the Project Scientist for a Flagship Mission, or the Principal Investigator for a competed mission) chooses the science team.

As we know, decades of research that show that people of all genders and races have unconscious bias against some underrepresented groups. Additionally, people tend to choose and hire people who remind them of themselves. These and a number of additional aspects of implicit bias mean that white men are still overrepresented at the tops of scientific and engineering fields.

When mission leaders strategize over how to get the most influential people on their teams (and thus also deprive any competing teams of the same expertise) their pool for selection is overwhelmingly white and male. Further, having served on successful missions makes it more likely that a given person will be chosen for additional missions, creating a positive feedback loop. Together these causes indicate several ways we can improve diversity on teams:

- Create a way to bring junior scientists onto teams in a permanent capacity. Now, graduate students and postdocs can generally only join a team when their primary advisor is on that team. They had to have chosen the right university and the right faculty member, decisions made perhaps before they knew they wanted to work on missions.
- Increasing diversity is not just about installing hiring rubrics. If the culture of the organization does not allow people to succeed based on their merits, then people from underrepresented groups will be lost preferentially, since they will lack the support that the majority feels.
- Talk about culture. Talk about norms: using increasing personal power to help others rather than aggrandize the self. Collegiality. Manners — leadership has to reprimand people for incorrect behavior. It starts from the top. Discuss how to run more egalitarian meetings, how to read body language, how to call on quiet people to share. Set up rewards for interdisciplinary work and success.
- Offer and value training in team-building and leadership starting in undergraduate programs and continuing throughout careers. Create, test, and iteratively improve leadership training for mission and project leads.

Appendix II

Additional Material for the Record

NASA'S SUBMITTED RESPONSES TO QUESTIONS ASKED DURING THE HEARING

Material requested for the record on page 70, line 1560, by Representative Webster during the July 18, 2017, hearing at which Dr. Jim Green and Dr. Robert Pappalardo testified.

The Radioisotope Thermal Generators (RTGs) on Voyager 1 and 2 currently produce about 250 watts each.

Material requested for the record on page 70, line 1563, by Representative Webster during the July 18, 2017, hearing at which Dr. Jim Green and Dr. Robert Pappalardo testified.

The spacecraft requires just above 200 watts of power to run the necessary systems to maintain its orientation and to communicate with Earth. The Voyagers lose approximately four watts per year through radioactive decay of the Plutonium 238 and reduced efficiency of the thermal interface. In roughly 13 years, insufficient wattage will require NASA to shut down the final instruments. At that point, the Voyagers will not be able to provide any scientific information of their environment.

Material requested for the record on page 71, line 1580, by Representative Webster during the July 18, 2017, hearing at which Dr. Jim Green and Dr. Robert Pappalardo testified.

The Voyagers will not in their foreseeable future be too far away for us to pick up their signal.