

ASTRONOMY, ASTROPHYSICS, AND ASTROBIOLOGY

JOINT HEARING

BEFORE THE

SUBCOMMITTEE ON SPACE &
SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY
COMMITTEE ON SCIENCE, SPACE, AND
TECHNOLOGY

HOUSE OF REPRESENTATIVES

ONE HUNDRED FOURTEENTH CONGRESS

SECOND SESSION

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ASTRONOMY, ASTROPHYSICS, AND ASTROBIOLOGY

TUESDAY, JULY 12, 2016

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

The subcommittees met, pursuant to call, at 10:11 a.m., in Room 2318, Rayburn House Office Building, Hon. Brian Babin [Chairman of the Subcommittee on Space] presiding.

LAMAR G. SMITH, Texas
CHAIRMAN

EDDIE BERNICE JOHNSON, Texas
RANKING MEMBER

Congress of the United States
House of Representatives

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

2321 RAYBURN HOUSE OFFICE BUILDING

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Astronomy, Astrophysics, and Astrobiology

Tuesday, July 12, 2016

10:00 a.m. – 12:00 a.m.

2318 Rayburn House Office Building

Witnesses

Dr. Paul Hertz, Director, Astrophysics Division, NASA

Dr. Jim Ulvestad, Director, Division of Astronomical Sciences, NSF

Dr. Angela Olinto, Chair, Astronomy and Astrophysics Advisory Committee (AAAC); Homer J. Livingston Professor, Department of Astronomy and Astrophysics, Enrico Fermi Institute, University of Chicago

Dr. Shelley Wright, Member, Breakthrough Listen Advisory Committee; Assistant Professor, University of California, San Diego; Member, Center for Astrophysics and Space Sciences, University of California, San Diego

Dr. Christine Jones, President, American Astronomical Society; Senior Astrophysicist, Smithsonian Astrophysical Observatory

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

Charter

TO: Members, Committee on Science, Space, and Technology
FROM: Majority Staff, Committee on Science, Space, and Technology
SUBJECT: Joint Subcommittee on Space and Subcommittee on Research and Technology
Hearing: "Astronomy, Astrophysics, and Astrobiology"
DATE: July 7th, 2016

On Tuesday, July 12th, 2016 at 10:00 a.m. in Room 2318 of the Rayburn House Office Building, the Committee on Science, Space, and Technology, Subcommittee on Space and Subcommittee on Research and Technology will hold a hearing titled, "Astronomy, Astrophysics, and Astrobiology."

Hearing Purpose

The hearing will examine space- and ground-based astronomy, astrophysics, and astrobiology programs, projects, and activities at NASA, NSF, academia, and the private sector.

Witnesses

- **Dr. Paul Hertz**, Director, Astrophysics Division, NASA;
- **Dr. Jim Ulvestad**, Director, Division of Astronomical Sciences, NSF;
- **Dr. Angela Olinto**, Chair, Astronomy and Astrophysics Advisory Committee (AAAC), and Homer J. Livingston Professor, Department of Astronomy and Astrophysics, Enrico Fermi Institute, University of Chicago;
- **Dr. Shelley Wright**, Assistant Professor, University of California, San Diego, Center for Astrophysics and Space Sciences, Breakthrough Listen Advisory Committee;
- **Dr. Christine Jones**, Senior Astrophysicist, Smithsonian Astrophysical Observatory, President, American Astronomical Society.

Staff Contact

For questions related to the hearing, please contact Mr. Tom Hammond, Staff Director, Space Subcommittee, Dr. Michael Mineiro, Counsel, Space Subcommittee, or Mr. Brian Corcoran, Policy Assistant, Space Subcommittee, at 202-225-6371.

Chairman BABIN. The Subcommittees on Space and Research and Technology will come to order. Without objection, the Chair is authorized to declare recesses of the subcommittees at any time.

Welcome to today's hearing entitled "Astronomy, Astrophysics, and Astrobiology." And now, I recognize myself for five minutes for an opening statement.

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

NASA has a long history of space-based astrophysics and astronomical science. Since the 1960s, NASA has operated space-based observatories. Among the most famous of these are the Hubble Space Telescope, which has produced some of the clearest images of the universe to date. The Hubble Space Telescope became the first of NASA's four Great Observatories, which aimed to observe the universe over the entire electromagnetic spectrum and would go on to include the Compton Gamma Ray Observatory, the Chandra X-ray Observatory, and the Spitzer Space Telescope.

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

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

In fiscal year 2016, NASA was appropriated approximately \$1.35 billion for astrophysics and astronomy. This investment of our tax dollars funds the operation and development of NASA's space-based observatories and the science that's it's produced. And while I believe that this is a worthwhile investment, I also have an obligation to ensure NASA's programs are administered wisely.

To that end, this Committee continues to closely monitor major NASA programs such as JWST and the Transiting Exoplanet Survey Satellite or TESS. As JWST and TESS progress through the critical integration and testing phase this year and next, I expect regular updates from NASA on progress made and the information about any potential issues well in advance.

The science priorities for NASA's astronomy and astrophysics activities are strongly informed by the National Academy of Sciences' decadal surveys. The priorities selected for the decade of 2012 to 2021, as outlined in the New Worlds, New Horizons in Astronomy and Astrophysics decadal survey, were to search for the first celestial bodies created in the universe and seek out nearby Earth-like planets suitable for habitation, and advance our understanding of astrophysics and the laws by which the universe operates. We are roughly halfway into the prescribed decadal and look forward to hearing about the progress we've made toward achieving these very goals.

Since the 2012 decadal, there have also been numerous scientific achievements that continue to inform NASA's astrophysics and astronomy programs. Perhaps one of the most remarkable achievements of the last several years is the discovery of Earth-like exoplanets orbiting distant suns. A little over two decades ago, the only planets known to mankind were those within our solar system. In the past decade, scientists have confirmed the existence of nearly 3,000 exoplanets throughout the universe, with at least eight of these exoplanets being roughly the size of Earth and residing in a habitable range of their stars.

This hearing also allows us an opportunity to inform the next decadal survey for astronomy and astrophysics for which NASA has already initiated studies. Outside organizations have already begun to discuss possibilities as well. And with the aforementioned discoveries of exoplanets and the likely operation of JWST in the coming years, there appears to be many areas ripe for future investigations.

It is also important to acknowledge the numerous scientific contributions made by private citizens, amateur astronomers, and non-government organizations. Citizen scientists conduct observations and analysis of vast astronomical data sets. This is a good thing because citizen science enhances public engagement and helps inspire the next generation of young students to pursue careers in astronomy, astrophysics, and astrobiology.

I want to thank today's witnesses for joining us as we discuss these very important issues, and I look forward to hearing each of your testimonies.

[The prepared statement of Chairman Babin follows:]



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

For Immediate Release
July 12, 2016

Media Contacts: Kristina Baum
(202) 225-6371

Statement of Space Subcommittee Chairman Brian Babin (R-Texas)
Astronomy, Astrophysics, and Astrobiology

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

NASA has a long history of space-based astrophysics and astronomical science. Since the 1960s, NASA has operated space-based observatories. Among the most famous of these are the Hubble Space Telescope, which has produced some of the clearest images of the Universe to date. The Hubble Space Telescope became the first of NASA's four Great Observatories, which aimed to observe the Universe over the entire electromagnetic spectrum and would go on to include the Compton Gamma Ray Observatory, the Chandra X-ray Observatory, and the Spitzer Space Telescope.

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While I believe that this is a worthwhile investment, I also have an obligation to ensure NASA's programs are administered wisely. To that end, this Committee continues to closely monitor major NASA programs, such as JWST and the Transiting Exoplanet Survey Satellite (TESS). As JWST and TESS progress through the critical integration and testing phase this year and next, I expect regular updates from NASA on progress made and information about any potential issues well in advance.

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It is also important to acknowledge the numerous scientific contributions made by private citizens, amateur astronomers, and non-government organizations. Citizen scientists conduct observations and analysis of vast astronomical data sets. This is a good thing because citizen science enhances public engagement and helps inspire the next generation of young students to pursue careers in astronomy, astrophysics and astrobiology.

I thank today's witnesses for joining us as we discuss these important issues and I look forward to hearing your testimony.

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Chairman BABIN. And now, before I recognize the Ranking Member, I would like to ask unanimous consent to enter into the record two letters relevant to the hearing submitted by the Association of Universities for Research and Astronomy and the Arecibo Science Advocacy Partnership. Without objection, I so order.

[The information appears in Appendix II]

Chairman BABIN. Now, I recognize the Ranking Member, the gentlewoman from Maryland, for an opening statement.

Ms. EDWARDS. Thank you very much. Good morning, Mr. Chairman. I appreciate that you're holding this hearing this morning on astronomy, astrophysics, and astrobiology. I want to also welcome our distinguished panel of witnesses this morning, and I apologize for our delay.

You know, throughout human history we've looked to the stars to measure the passage of time, to navigate our ships, and to decide when to plant our crops. While the study of the night sky has practical benefits to society, its real value is far less tangible but not less important. Astronomy opens our eyes. It offers a new way to look at the world. And when Copernicus discovered that the Earth orbits the sun, it started a revolution. And when astronomers discovered that stars are made of the same elements as we are, it deepened our connection to stars and galaxies that are unimaginably far away.

The recent explosion in exoplanet discoveries has brought us closer to finding out if life is common or rare throughout the universe. Many fundamental questions remain, and it's our job to ensure that scientists have the tools they need to address them.

In February this Committee held a hearing to celebrate and learn more about the first-ever detection of gravitational waves. If we learned anything, it's that investing in science, even when there is no foreseeable concrete benefit to society, does indeed pay off. Large telescopes like the James Webb Space Telescope and Wide Field Infrared Survey Telescope, the Large Synoptic Survey Telescope, are critical to the next generation of astronomers.

We often express our support for science, engineering, technology and math education, but those efforts are wasted if we don't make decisions now to ensure the development of researchers, facilities, and missions that will enable them to do their work. Astronomical discoveries resonate with the basic human drive to understand our surroundings. The awe they inspire is perhaps the reason that astronomy is one of the most accessible fields of science to the general public. Astronomy serves as a gateway for students who may not otherwise enter a science discipline. And every year nearly 400 students receive bachelor's degrees in astronomy. Many students who start out studying astronomy go on to pursue careers in medicine, engineering, and data science.

In addition to attracting more students to study science, astronomy inspires members of the public to pay attention and even to participate in astronomy. The Hubble Space Telescope made a huge impact on the public's engagement in astronomy. It is often called "the people's telescope" because its beautiful images brought the awe-inspiring sights of the cosmos into classrooms and living rooms around the world.

Citizen science has deep roots in astronomy. Amateur astronomers have discovered supernova, comets, and asteroids and even exoplanets. With the advent of the Internet, an even broader group of the public is now able to contribute to research efforts led by the astronomy community.

This morning's hearing will give us a chance to discuss the compelling questions astronomers have dedicated their careers to answering, as well as the programs, facilities, and missions that are necessary to enable their investigation into those questions.

We live in an era of multi-messenger astronomy. We can see the universe with light, with particles, and now with gravitational waves. And as we look ahead, we must acknowledge that the measurements that are required to advance future astronomical investigations are rapidly evolving. We need to plan ahead to ensure that development of cutting-edge detectors and analysis software keeps pace with the needs of scientists.

We have the chance to speak to the leaders of the astronomy community today and to find out where astronomy is going. And one thing is clear. We in Congress need to provide the resources needed to ensure that all areas of science, including astronomy, can continue to carry out groundbreaking discoveries in the years to come.

And again, I'd like to thank our witnesses for being here, and I look forward to your testimony.

And I also want to acknowledge by my side today are staff Sara Barber who is a fellow with us and has about six weeks, and I told her how lucky she was that, as an astronomer, she gets to be at this hearing.

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

[The prepared statement of Ms. Edwards follows:]

OPENING STATEMENT
Ranking Member Donna F. Edwards (D-MD)
of the Subcommittee on Space

House Committee on Science, Space, and Technology
 Subcommittee on Space
 Subcommittee on Research and Technology
"Astronomy, Astrophysics, and Astrobiology"
 July 12, 2016

Good morning and thank you, Mr. Chairman, for holding this hearing on "*Astronomy, Astrophysics, and Astrobiology*". Welcome to our distinguished panel of witnesses.

Throughout human history we have looked to the stars to measure the passage of time, navigate our ships, and decide when to plant our crops. While the study of the night sky has practical benefits to society, its real value is far less tangible but no less important.

Astronomy opens our eyes and offers us a new way to look at the world. When Copernicus discovered that the Earth orbits the Sun, it started a revolution. When astronomers discovered that stars are made of the same elements as we are, it deepened our connection to stars and galaxies that are unimaginably far away. The recent explosion in exoplanet discoveries has brought us closer to finding out if life is common or rare throughout the universe.

Many fundamental questions remain, and it is our job to ensure that scientists have the tools they need to address them. In February, this committee held a hearing to celebrate and learn more about the first ever detection of gravitational waves by the LIGO facility. If LIGO taught us anything, it is that investing in science, even when there is no foreseeable concrete benefit to society, pays off.

Large telescopes like the James Webb Space Telescope, the Wide-Field Infrared Survey Telescope, and Large Synoptic Survey Telescope are critical to the next generation of astronomers. We often express our support for science, technology, engineering, and math education, but those efforts are wasted if we don't make decisions now to ensure the development of the researchers, facilities and missions that will enable them to do their work.

Astronomical discoveries resonate with the basic human drive to understand our surroundings. The awe they inspire is perhaps the reason that astronomy is one of the most accessible fields of science to the general public.

Astronomy serves as a gateway for students who may not otherwise enter a science discipline. Every year, nearly 400 students receive bachelor's degrees in astronomy. Many students who start out studying astronomy go on to pursue careers in medicine, engineering, and data science.

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One thing is clear. We, in Congress, need to provide the resources needed to ensure that all areas of science, including astronomy, can continue to carry out ground-breaking discoveries in the years to come.

Again, I'd like to thank our witnesses for being here and I look forward to your testimony.

Thank you Mr. Chairman, and I yield back.

Chairman BABIN. Yes, ma'am. Thank you.

I'd like to recognize one of my interns out there, a student from Texas A&M University from my hometown of Woodville, Texas, and that's Miss Sarah Reese. Good to have you, Sarah.

Ms. EDWARDS. Both Sarahs.

Chairman BABIN. That's right.

Now, I'd like to introduce the Chairwoman on the Subcommittee on Research and Technology, Mrs. Comstock, the gentlewoman from Virginia.

Mrs. COMSTOCK. Thank you, Mr. Chairman. And I also welcome your A&M student. I have family down in Bryan, Texas, so a great university there.

Since 2000, seven of the eight people to receive Nobel Prizes for astrophysics work have been American scientists. The United States has had tremendous achievements in astrophysics and astrobiology research. Taxpayer-supported grants from the National Science Foundation fund much of this groundbreaking research. In fiscal year 2016, NSF will spend over \$246 million to support the astronomical sciences. That money goes toward an incredible variety of projects, from funding facilities like the Green Bank Telescope in West Virginia, to small research grants given to faculty and students at universities around the country.

It has been a productive year for federally funded astrophysics research. The biggest achievement was the detection of gravitational waves at the LIGO Observatory, this past September, proving part of Einstein's theory of relativity. Just a couple of weeks ago, LIGO announced a second discovery. This amazing project was able to detect ripples in space-time caused by a collision of black holes 1.3 billion light years away from fields in Washington and Louisiana. LIGO and its predecessors have been funded by NSF for over 30 years, and its top scientists will almost certainly receive a Nobel Prize.

Some of NSF's most interesting astronomy projects are still in the works. The Large Synoptic Survey Telescope, or LSST, will produce an incredibly detailed picture of the full night sky every three nights for a decade. It will make its findings available to the public as it goes along, resulting in the world's largest public data set. And I think this is particularly exciting when you look at all these projects and how the public can participate, how all of our online capacity can bring this into every classroom, every part of the country, really every part of the world, wherever there might be some kind of device that can view it on and interact. And that's a really exciting aspect of it.

The Daniel K. Inouye Solar Telescope is another important upcoming project. Scheduled to start operating in 2018 in Hawaii, it will produce the most detailed images of the sun ever by a ground-based device. NSF-funded astronomy programs are among the largest sources of international collaboration for American scientists. In particular, the Gemini Observatory and the Atacama Large Millimeter Array are multinational projects which each involve at least five nations and would not be possible for any of them to accomplish individually.

Still, NSF's astronomy program faces questions going forward. The Arecibo Observatory, long one of the premier sites it funds in

Puerto Rico, is nearing the end of its lifecycle. NSF needs to decide what it will do with the facility, which many in the scientific community believe can still contribute to furthering scientific discoveries and providing education opportunities.

It is in our nation's best interest to continue our commitment to researching the fundamental nature of the universe. Breakthroughs like the detection of gravitational waves inspire the next generation of scientists.

For the American economy to be successful in the 21st Century, we need to have that skilled labor force and workforce that understands innovation and emerging technologies and leads.

And I wanted to particularly note today I'm very pleased to see the balance of women here in our panel. Having passed the INSPIRE Act here earlier on this Committee, it's really—actually, you're outnumbering the men today, so that's particularly exciting also. So we're really look forward to you inspiring the next generation of leaders, and I look forward to hearing from this panel of accomplished witnesses this morning, one of whom directs all astronomical science projects at NSF. So thank you.

[The prepared statement of Mrs. Comstock follows:]



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

For Immediate Release
July 12, 2016

Media Contacts: Kristina Baum
(202) 225-6371

Statement of Research and Technology Subcommittee Chairwoman Barbara Comstock (R-Va.)

Astronomy, Astrophysics, and Astrobiology

Chairwoman Comstock: Since 2000, 7 of the 8 people to receive Nobel Prizes for astrophysics work have been American scientists. The United States leads in science—we have had tremendous achievements in astrophysics and astrobiology research.

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That money goes toward an incredible variety of projects - from funding facilities like the Green Bank Telescope in West Virginia, to small research grants given to faculty and students at universities around the country.

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I look forward to hearing from our panel of accomplished witnesses this morning, one of whom directs all astronomical science projects at NSF.

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Chairman BABIN. Thank you, Chairwoman Comstock.

Now, I'd like to recognize the Chairman of our Full Committee, the gentleman from Texas, Chairman Smith.

Chairman SMITH. Thank you, Chairman Babin.

The science of astronomy goes back millennia and is one of the oldest of the natural sciences. Astrophysics, the application of physics to understand the nature of the universe, is a relatively new scientific field that has blossomed in the last few years.

Space-based observations from telescopes like the Hubble Space Telescope have amazed us for decades, and the James Webb Space Telescope is only a couple of years away from launch. Recently, we have seen amazing discoveries of planets outside our solar system and the detection of gravitation waves. This is just the beginning. Many more amazing discoveries await us.

NASA's Chief Scientist, Dr. Ellen Stofan, recently testified before this Committee that "with future technology and instruments currently under development, we will explore the solar system and beyond, and could indeed—perhaps in as little as 10–20 years—discover some form of life, past or present."

Since 1995, over 3,000 exoplanets have been identified, with several found to be in the "habitable zone" where a planet with sufficient atmospheric pressure can maintain liquid water on its surface. The Kepler spacecraft discovered many of these exoplanets and led scientists to estimate that as many as 11 billion rocky, Earth-sized exoplanets could be orbiting in the habitable zones of sun-like stars in the Milky Way alone.

Kepler's successes in hunting exoplanets will continue with the launch of the Transiting Exoplanet Survey Satellite in 2017 and be augmented by the capabilities of the James Webb Space Telescope, the Wide Field Infrared Space Telescope, and ground-based telescopes such as the Large Synoptic Survey Telescope, or LSST. The LSST may be able to peer into the atmospheres of these exoplanets and conduct spectroscopy to determine the composition of their atmospheres.

While partnerships between the private and public sector in astronomy are well established, these ties need to be strengthened when it comes to exoplanet surveys and exploration related to astrobiology. Private sector groups like the Breakthrough Listen project provide funding opportunities to leverage limited government funding to maximize discovery.

Going forward, I hope that NASA, NSF, and academia will expand public-private partnerships to advance optical laser transmission surveys, as it is a promising and exciting field of inquiry.

Mr. Chairman, I look forward to our witnesses' testimony today. With representation from the NASA, the NSF, the Astronomy and Astrophysics Advisory Committee, the American Astronomical Society, and the Breakthrough Listen Project, we have the opportunity to hear a number of perspectives on the subjects of astronomy, astrophysics, and astrobiology.

Thank you and yield back.

[The prepared statement of Chairman Smith follows:]



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

For Immediate Release
July 12, 2016

Media Contacts: Kristina Baum
(202) 225-6371

Statement of Chairman Lamar Smith (R-Texas)
Astronomy, Astrophysics, and Astrobiology

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Chairman BABIN. Thank you, Mr. Chairman.

Now, I'd like to recognize the gentlewoman from Maryland for a statement on behalf of Ranking Member Johnson.

Ms. EDWARDS. Thank you, Mr. Chairman.

Just for the record, we've entered the Ranking Member Eddie Bernice Johnson's statement in the record today, and she regrets that she is not able to be here today. She is attending the memorial service in Dallas today. Thank you. And I yield back.

[The prepared statement of Ms. Johnson follows:]

OPENING STATEMENT

Ranking Member Eddie Bernice Johnson (D-TX)

House Committee on Science, Space, and Technology
 Subcommittee on Space
 Subcommittee on Research and Technology
"Astronomy, Astrophysics, and Astrobiology"
 July 12, 2016

Thank you Chairman Babin and Chairwoman Comstock for holding this hearing, and thank you to the esteemed panel of witnesses for being here this morning.

Astronomy, astrophysics, and astrobiology are scientific fields that inspire young and old alike-- those who have experienced the beauty of the night sky with their naked eye alone; those who have peered through the world's most powerful telescopes; those who have no formal STEM training, and those who have dedicated their lives to studying the deepest questions of the universe. Indeed, the questions that inspire the pursuit of astronomy, astrophysics, and astrobiology-- what are the origins of the universe, what is dark matter, are we alone -- captivate us all.

The United States has long been a leader in astronomy and astrophysics. Through our Federal agencies -- NASA, the National Science Foundation (NSF), and the Department of Energy (DOE) -- and their university, non-profit, and private sector partners, we have led the development and construction of many of the world's most important astronomical facilities, including the Hubble Space Telescope, LIGO, and ALMA.

As we all know, these facilities can be extraordinarily expensive, in some cases costing billions of dollars over the full life cycle of design, construction, deployment, and operations. We have made a collective decision as a nation that these investments are worthwhile. Hearings like this one serve as an important opportunity to remind us of why we've stood by that decision, and to ensure that the investments we are currently making remain on track.

In the Science, Space, and Technology Committee, we have a unique perspective and responsibility because of our role in overseeing the three main agencies whose missions include support for astronomy, astrophysics, and astrobiology. These fields are somewhat unique in the federal research portfolio in terms of all of the collaboration and coordination that occurs across three separate dimensions: between the community of users and the agencies, among the agencies themselves, and between our government and our international partners.

In this hearing, we will have the opportunity to discuss astronomy and astrophysics across all three of those dimensions. We will hear about some of the opportunities and challenges, as well as the current state of horizon planning, including planning for the computational power and integrated databases that will maximize the scientific value of the vast streams of data yet to come.

By all accounts, NASA, NSF, and DOE are doing a remarkable job with all of this in a tough budget environment, and I want to commend them for that. However, we also know that at a time

in which facilities are becoming more and more expensive to build and operate, agencies are struggling to fund the researchers themselves. Proposal success rates are dropping, and promising early career astronomers are deciding to pursue other career paths. Astronomers are so well trained that they are highly sought-after in many other fields of research and sectors of our economy. That is something to celebrate. However, we must be careful not to chase the most promising early career astronomers out of a field they love because we fail to provide the funding to support their important work. It is in the interest of our nation that we maintain a vibrant scientific enterprise across all fields of science and engineering – to satisfy human curiosity and advance knowledge, to lead in innovation, and to continually strengthen our economic, environmental, and national security.

Chairman BABIN. Thank you. Now, let me introduce our witnesses for today's hearing. And our first witness today is Dr. Paul Hertz, Director of the Astrophysics Division at NASA. Dr. Hertz is responsible for the agency's research programs and missions necessary to discover how the universe works and explore how the universe began and developed into its present form and to search for Earth-like planets. Dr. Hertz received a B.S. degree in both physics and mathematics from MIT followed by a Ph.D. from Harvard University in astronomy.

Our second witness today is Dr. Jim Ulvestad. I hope I pronounced that right.

Dr. ULVESTAD. Ulvestad.

Chairman BABIN. Okay. Ulvestad. Is that it?

Dr. ULVESTAD. Ulvestad.

Chairman BABIN. Ulvestad, okay. Jim Ulvestad, Director of the Division of Astronomical Sciences at NSF. In this role he leads a staff of 25 and oversees an annual budget of \$246 million plus major observatory construction projects with an additional budget of \$100 million in fiscal year 2016. He earned a bachelor's degree from the University of California at Los Angeles and a Ph.D. in astronomy from the University of Maryland.

Our third witness today is Dr. Angela Olinto, Chair of the Astronomy and Astrophysics Advisory Committee, or AAAC, and the Homer J. Livingston professor in the Department of Astronomy and Astrophysics at the Enrico Fermi Institute at the University of Chicago. Dr. Olinto is the principal investigator of the Extreme Universe Space Observatory on a super pressure balloon mission and a member of the international collaboration of the Pierre Auger Observatory. She received her bachelor of science in physics from the Pontificia Universidad Catolica of Rio de Janeiro in Brazil and her Ph.D. in physics from MIT.

Our fourth witness is Dr. Shelley Wright, member of the Breakthrough Listen Advisory Committee and assistant professor at the University of California in San Diego. Dr. Wright has extensive experience working with optical infrared instrumentation with a particular focus on imaging cameras and spectrographs that operate behind adaptive optics systems on large telescopes. She currently serves as project scientist for the first light instrument or IRIS for the future Thirty Meter Telescope. Dr. Wright received her bachelor of science in physics at the University of California in Santa Cruz and her Ph.D. from UCLA.

Our final witness of today is Dr. Christine Jones, who is President of the Astronomical American astronomical Society and senior astrophysicist at the Smithsonian Astrophysical Observatory. Throughout her career, Dr. Jones is worked on a variety of research topics, but most recently her research is focused on x-ray studies of the hot gas and galaxies and galaxy clusters using the Chandra X-ray Observatory. Dr. Jones earned her A.B., her M.A., and her Ph.D. degrees in astronomy at Harvard University.

So thank you all, distinguished witnesses, for being here today. And I now recognize Dr. Hertz for five minutes to present his testimony.

**TESTIMONY OF DR. PAUL HERTZ, DIRECTOR,
ASTROPHYSICS DIVISION, NASA**

Dr. HERTZ. Thank you, Mr. Chair.

Members of the Committee, I am pleased to appear before you to discuss the current and future astrophysics programs at NASA.

How did our universe begin and evolve? How did the familiar night sky of galaxies, stars, and planets come to be? And are we alone in the universe? These are the enduring questions that humankind has been asking since we first looked up at the sky, and now, for the first time, we are able to answer those questions scientifically. We're probing back in time with the Hubble Space Telescope detecting faint infrared signals from galaxies that formed 13 billion years ago, only 400 million years after the Big Bang.

Hubble and the Chandra X-ray Observatory are working to gather to study supermassive black holes showing how they formed in the early universe and how they triggered birth of stars and galaxies. And NASA is developing two new space observatories to further advance our understanding of the cosmos: the James Webb Space Telescope, which will launch in 2018, will detect the light from the first stars and galaxies that formed after the Big Bang; and the Wide Field Infrared Survey Telescope, or WFIRST, will launch in the mid-2020s and help us understand the mysterious dark energy that is propelling the acceleration of our universe.

Understanding the origins of galaxies and stars leads us to an understanding of how planets formed, including planets capable of supporting life. Our knowledge of planets outside of our solar system, exoplanets, has exploded in the last 20 years. Thanks to the pioneering discoveries made with ground-based observatories followed by the Kepler Space Telescope, we now know that planets orbiting other stars are common. For four years Kepler measured the light from 150,000 stars staring at them 24 hours a day, seven days a week, 365 days a year and discovered at least 5,000 exoplanet candidates around those stars.

The exoplanets discovered so far are astounding in their diversity. One is a rocky hot planet locked by gravity with one side always facing its star, wild swings in temperature that hint at a surface bubbling with rivers of lava. Another is a scorching alien world where it rains glass sideways with winds of 4,500 miles per hour. And another is half the size of Jupiter but speeds around its star in only four days instead of the leisurely 12 years that Jupiter takes to orbit our sun.

Hubble Space Telescope has detected the most distant exoplanet known and has measured the atmospheric composition of many exoplanets using the parent star's light filtered through the exoplanet's atmosphere. And the Spitzer Space Telescope has probed the temperature and atmospheric composition and even weather on distant exoplanets.

But the most compelling search is for the rocky planets that, like the Earth, might be capable of supporting life. To date we have found nine roughly Earth-sized planets located in the habitable zone of their parent stars, but this type of planet lies at the limits of what we can discover using our current generation of space telescopes. The Webb telescope will examine the makeup of known

exoplanets through both transit spectroscopy and direct imaging. And the new observatories coming online will discover new exoplanets for study by Webb: the Transiting Exoplanet Survey Satellite test and the previously mentioned WFIRST.

Now, one thing that Hubble, Chandra, Spitzer, Webb, and WFIRST all have in common is that they were recommended by a decadal survey. As the time approaches for the next decadal survey, NASA has initiated mission concept studies to inform the next decadal survey's deliberations.

Following the recommendations of our advisory groups, we have identified four large mission concepts to study. What type of science might we expect from future NASA space observatories? An x-ray surveyor might discover the first generation of supermassive black holes and explain in the early universe and determine the influence of dark matter on the evolution. A far infrared surveyor might find biosignatures in the atmospheres of exoplanets and explain the origins of the dust and molecules that serve as the prerequisites for life. An ultraviolet visible infrared surveyor with a large mirror might capture the first starlight in the early universe, detect water worlds and biomarkers on distant Earth-like planets and image the icy plumes from moons of giant planets in our own solar system. An inhabitable exoplanet imaging mission might search for signs of habitability in the atmospheres of planets orbiting stars in our Milky Way galaxy.

We're fortunate to live during a time when grand scientific quests are possible and in a country that values the curiosity and discovery as inherently noble pursuits. And at NASA we're thankful to Congress for its continued support.

So thank you, and I'll be pleased to answer any questions the Committee might have.

[The prepared statement of Dr. Hertz follows:]

HOLD FOR RELEASE UNTIL PRESENTED
BY WITNESS
July 12, 2016

Statement of

Dr. Paul Hertz
Director, Astrophysics Division
Science Mission Directorate
National Aeronautics and Space Administration

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

Chairman Babin, Chairwoman Comstock, Ranking Member Edwards, Ranking Member Lipinski, and Members of the Subcommittees, I am pleased to have the opportunity to appear before you to discuss astrophysics research underway at NASA and our roadmap to the future.

Enduring Questions

How did our universe begin and evolve? How did the familiar night sky of galaxies, stars, and planets come to be? And, one of the greatest questions of all time, are we alone in the universe?

These are the enduring questions of humanity. For the first time in human history, we are capable of answering these questions scientifically. We are answering these questions by making precise measurements of the universe using the world's most capable collection of space observatories. We are probing back in time with the Hubble Space Telescope by detecting exquisitely faint infrared signals from galaxies that formed about 13 billion years ago – only 400 million years after the Big Bang and ever closer to the beginning of time. We are fine tuning our calculation of the expansion rate of the universe and the properties of dark energy by refining the measured distance to remote galaxies with Hubble and by weighing the million degree gas in distant clusters of galaxies with the Chandra X-ray Observatory. Chandra and the Fermi Gamma-ray Space Telescope are observing high energy photons from very distant quasars in order to set limits on the nature of the “space-time foam” – a feature predicted by quantum mechanics about the roughness of space and time at sub-atomic scales. Hubble and Chandra work together to gather evidence about the nature of supermassive black holes, including data showing how they formed in the early universe and how they triggered the birth of new stars in the first galaxies. The Nuclear Spectroscopic Telescope Array is peering through the thick blankets of gas and dust in the most active galaxies to reveal the most massive known black holes at their centers.

NASA's space observatories are used by astronomers from around the world to make fundamental discoveries about the universe we live in. Every two years, these missions are

reviewed by a panel of senior astronomers to confirm that their continued operation is cost effective and scientifically productive. In June 2016, following a thorough Senior Review, NASA approved all of these missions to continue their science operations for another two years, contingent on the Astrophysics Division receiving the funding requested in the FY 2017 President's Budget Request.

NASA is developing two new missions to advance our understanding of the universe. The James Webb Space Telescope, launching in 2018, will observe the first stars and galaxies formed after the Big Bang. The Wide-field Infrared Survey Telescope, or WFIRST, launching in the mid-2020s, will measure the expansion history of the universe and constrain the properties of the dark energy that is accelerating that expansion.

Learning about the origins of the universe – how it began and how it evolved, is critical to understanding how planets formed and whether planets could evolve that are capable of harboring life.

Exoplanets

Our knowledge of planets outside of our solar system, or exoplanets, has exploded in the last twenty years. From antiquity through almost the entire twentieth century, people wondered and dreamed about life beyond Earth without knowing whether planets orbiting other stars were common or rare. Thanks to pioneering discoveries made with ground based observatories, followed by the Kepler Space Telescope mission, we now know that planets orbiting other stars are common. Not only is the Sun not unique in having a planetary system, but most of the stars in the sky have planetary systems of their own. Future generations will look at the night sky in a completely different way than we did when we were young. Where we once may have guessed whether or not there were unknown worlds waiting to be discovered, our children will grow up knowing that there are billions and billions of planets in our Galaxy.

How have we learned this? By using the same methods that we always use to solve the mysteries of the universe – by determining what measurements are needed to advance our knowledge, developing innovative new instruments capable of making those measurements, by designing new telescopes that collect the light needed for those discoveries, and then by careful analysis and attention to detail to eliminate sources of error. In this case, the Kepler team detected thousands of exoplanets using a method that was developed by noticing that the light from some stars dims just a tiny bit in a regular way. The Kepler Space Telescope is an example of this. Kepler detects exoplanets by measuring the tiny, periodic dimming caused by planets crossing in front of their parent stars. Some have likened this to standing on the steps of the Capitol Building and attempting to observe a ladybug crossing in front of a lighthouse in Washington state. The measurement needed is a tiny change in the brightness of a star, the innovative new instrument is an ultraprecise photometer, the telescope is one that can point at the same stars for years on end without wobbling, and the careful data analysis must separate the dimming caused by exoplanets from all other possible reasons for the starlight to vary. For four straight years, Kepler continuously measured the light from each of the 150,000 stars in its field-of-view and discovered over 5,000 exoplanet candidates.

While Kepler was NASA's first mission dedicated to the search for exoplanets, and the first capable of detecting Earth-size exoplanets orbiting a Sun-like star, it is not NASA's only mission involved in the search. Hubble's sharp vision has been used to detect some of the farthest planets that have ever been found and to determine their atmospheric composition by observing the parent star's light filtered through the exoplanet's atmosphere. Spitzer has used the same technique of transit spectroscopy to determine the temperature and atmospheric compositions of several distant exoplanets.

The exoplanets discovered so far are astounding in the diversity of their size and characteristics. HAT-P-11b is about the size of Neptune, with an atmosphere laden with water vapor. 55 Cancri e (Janssen) is a hot, rocky planet locked by gravity with one side always facing its star and the other permanently plunged in darkness; wild swings in temperature hint at a surface that may be bubbling with rivers of lava. HD 189733b is a scorching alien world, where it possibly rains glass – sideways – in howling 4,500 mph winds. 51 Pegasi b (Dimidium) is about half of the mass of Jupiter, but speeds around its sun in a blistering four days instead of the twelve years that it takes Jupiter to make an orbit. We now know that tidally locked planets and “hot Jupiters” are very common in the universe, although we have nothing like them in our solar system. But the most compelling search is for a type of planet found in our solar system – one that, like the Earth, is capable of supporting life.

To find such habitable exoplanets, we are looking for planets that are the right size – planets that are not so big that they have miles-deep, high pressure atmospheres, and not so small that they cannot retain an atmosphere – and the right temperature. They must receive the right amount of heat from their star to support liquid water – not too hot and not too cold. To date, we have found nine roughly Earth-sized planets in the habitable zone of their parent stars, but this type of planet lies at the very boundary of what is detectable by our current fleet of telescopes. The exoplanets discovered by Kepler are generally too far away to allow detailed follow-up studies of their atmospheric composition.

We eagerly await the launch of the James Webb Space Telescope in 2018 to probe deeper into the origins of the universe and to carefully examine the makeup of known exoplanets through both transit spectroscopy and direct imaging. And two new observatories coming on line will contribute to our search for exoplanets: TESS, the transiting exoplanet survey satellite, and WFIRST, the wide-field infrared survey telescope.

Upcoming Missions

TESS will launch in 2017 or 2018 and will use Kepler's transit method to search for exoplanets around the nearest and brightest stars in the sky. TESS will provide a catalog of the many types of exoplanets that are out there. These exoplanets will be among the best targets for further study. Many of the stars that TESS observes will be smaller than the Sun; this makes it easier to find rocky exoplanets in the habitable zone. Exoplanets orbiting bright stars are the best candidates for using the Webb Telescope to measure their atmospheric composition. Exoplanets orbiting the nearest stars are the best candidates for direct imaging using a coronagraph, such as the one that WFIRST will have.

WFIRST, in addition to studying dark energy, will carry a revolutionary coronagraph instrument that will block the light of stars to let us see directly see exoplanets and measure their light. The WFIRST coronagraph instrument will be capable of seeing exoplanets that are up to one billion times fainter than their parent star. For the first time, we will be able to measure the light directly from an exoplanet like Jupiter or Neptune in our solar system. Although not sensitive enough to see an Earth-like planet, the WFIRST coronagraph will demonstrate the technology needed to accomplish that measurement when coupled with a larger telescope.

A Steady Cadence of Missions

For over forty years we have used the Decadal Survey process to determine the most compelling science questions to be addressed in the next decade. This process is managed by the National Academy of Sciences, which brings together America's leading scientists to recommend a course of exploration for the next decade. The Decadal Survey named Hubble as the highest priority large space mission in 1972, Chandra in 1982, and Spitzer in 1991; all have fundamentally changed the way we understand the universe and continue to produce world-class science. Our next large observatories were also top recommendations of the Decadal Survey: Webb in 2001, and WFIRST in the most recent study, in 2010.

As the time approaches to conduct the next Decadal Survey, we are initiating mission concept studies that will provide solid information to help the Decadal Survey Committee make informed decisions. At the recommendation of our advisory groups, we have identified four large mission concepts to study. Teams have been formed to study each of these mission concepts to determine what science could and should be done, what new technologies exist to enable new discoveries, what technology is needed, what these new missions might look like, and what these new missions might cost. We will also form teams soon to study medium-size mission concepts, and all of this information will be provided to the decadal survey team. While our current study activities are focused on medium and large-sized missions (given the long lead time needed to develop the concepts and technologies associated with them), we continue to support a balanced portfolio that also includes competed smaller missions.

What type of science might we expect from future NASA space observatories?

An x-ray surveyor might discover the first generation of supermassive black holes in the infant universe, unravel the structure of the cosmic web and determine its impact on the evolution of galaxies, and determine the influence of dark matter on the evolution of the universe.

A far-infrared surveyor might find bio-signatures in the atmosphere of exoplanets (perhaps methane, ozone, or carbon dioxide, which could indicate the presence of life), map the beginnings of chemistry, and explain the origins of dust and the molecules that form the cradle of life.

An ultraviolet/visible/infrared surveyor could be designed with a very large mirror that could capture the first starlight in the early universe, map the distribution of nearby dark matter with unprecedented resolution, detect water worlds and biomarkers on distant Earth-like planets, and image icy plumes from the moons of giant planets in our solar system.

And a habitable exoplanet imaging mission could search for signs of habitability in the atmospheres of exoplanets.

In addition, in 2017 NASA will initiate studies of medium-size Astrophysics Probe missions. The astrophysics community has informed NASA that such missions could be capable of compelling astrophysics research with more modest capabilities than the large missions already under study.

NASA's portfolio of future observatories will also include small, Principal Investigator-led missions selected through competitive announcements of opportunity within the Explorers Program. NASA is targeting the release of a draft Announcement of Opportunity (AO) for a medium-class Astrophysics Explorer and related solicitation for a Mission of Opportunity (MoO) in early Summer 2016, and releasing the final AO and MoO solicitation in late Summer/early Fall 2016.

Summary

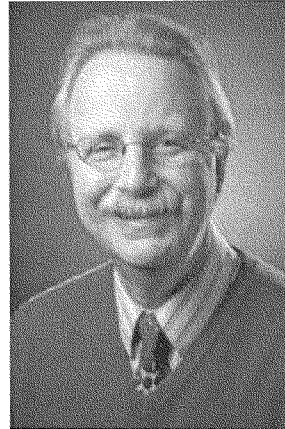
Like Hubble, Chandra, Spitzer, Fermi, Kepler, and NuSTAR before them, the James Webb Space Telescope, the Transiting Exoplanet Survey Satellite, and the Wide Field Infrared Survey Telescope will fundamentally alter our understanding of the universe and our place in it. We are generating ideas now that the next Decadal Survey Committee will need to recommend the science that will carry us even further – whether to explore deeper in time to the origins of our universe, to unlock the hidden universe of dark matter, or to detect evidence of life beyond our solar system. Regardless of our path, it is certain that we will continue to push boundaries to answer humanity's enduring questions.

We are fortunate to live in a country that values curiosity and discovery as inherently noble quests. We are fortunate to have a national workforce that is capable of innovation and spectacular achievements. And at NASA we are thankful to Congress for affording us the opportunity to answer some of humanity's most fundamental questions.

Thank you for listening, and I would be happy to answer any questions you have.

DR. PAUL HERTZ, ASTROPHYSICS DIVISION DIRECTOR

Paul Hertz was named Director of the Astrophysics Division in the Science Mission Directorate at NASA in March 2012. He is responsible for the Agency's research programs and missions necessary to discover how the universe works, explore how the universe began and developed into its present form, and search for Earth-like planets. He previously served as the Chief Scientist of NASA's Science Mission Directorate, managing the Directorate's science solicitation activities and ensuring the scientific integrity of the Directorate's programs. During that period, he oversaw the acquisition of more than \$3B of space flight missions and instruments for projects across the breadth of NASA's space and Earth science programs. Dr. Hertz joined the NASA Office of Space Science as a Senior Scientist in 2000 and managed projects and programs in astrophysics and planetary science.



Dr. Hertz received SB degrees in both Physics and Mathematics from MIT, followed by a PhD from Harvard University in Astronomy in 1983. He then joined the staff of the Naval Research Laboratory in Washington DC as an astrophysicist, a position he held until joining NASA in 2000. Dr. Hertz's research concentrated on X-ray emission from galactic neutron stars, black holes, and globular clusters. He authored or co-authored over 100 papers, including observational papers in every band of the electromagnetic spectrum from radio to gamma ray as well as theory and computation papers. From 1993-2001 he was Associate Professor of Computational Sciences and Space Sciences at George Mason University. Dr. Hertz is a recipient of the Meritorious Presidential Rank Award, the Robert J. Trumpler Award of the Astronomical Society of the Pacific, the Alan Berman Research Publication Award of the Naval Research Laboratory (twice), and multiple NASA Group Achievement Awards.

Dr. Hertz is married with three children. He has a passion for baseball which he exercises by leading his coworkers on annual treks to attend games at Nationals Park. In 2004, Dr. Hertz met the Orioles Bird when he was honored by the Baltimore Orioles as a "Heavy Hitter." In 2006, he made his Broadway debut as Contestant #28 in "The 25th Annual Putnam County Spelling Bee." He made his Hollywood debut as a Nationals fan in the 2010 James L. Brooks film "How Do You Know." In 2011, Dr. Hertz received the Washington Nationals' Spirit Award during a pre-game ceremony hosted by the team's mascot, Screech. He threw out the first pitch at Nationals Park before the September 1, 2012, game between the St. Louis Cardinals and the Washington Nationals.

Chairman BABIN. Thank you, Dr. Hertz.
Now, I'd like to recognize Dr. Ulvestad for his opening statement.

**TESTIMONY OF DR. JIM ULVESTAD, DIRECTOR,
DIVISION OF ASTRONOMICAL SCIENCES, NSF**

Dr. ULVESTAD. Thank you, Chairman. Chairman Babin, Ranking Member Edwards, Chairwoman Comstock, Chairman Smith, and members of the subcommittees, we thank you for the opportunity for the National Science Foundation to discuss the exciting progress in astronomy, astrophysics, and astrobiology and the outlook for the future. This remarkable progress is the product of sustained taxpayer support through representatives such as yourselves and the long-term effort of the basic research community represented here on my left.

For millennia, humans have viewed light from the sky to learn about the universe. Today, we observe across the electromagnetic spectrum from radio waves to gamma rays and are ready to look at the universe in new ways. Particles such as neutrinos and cosmic rays provide a different view, and gravitational waves give yet another.

In this new era of multi-messenger astrophysics, NSF has a leadership role. The sixth Astronomy and Astrophysics Decadal Survey was delivered in 2010 by the National Academies. The survey stressed the importance of supporting individual investigator research, as well as developing forefront observatories.

Three principal science areas were identified: cosmic dawn, searching for the first stars, galaxies, and black holes; new worlds, seeking nearby habitable planets; and physics of the universe, understanding scientific principles. These scientific areas represent enduring human quests. Take new worlds as an example. The Atacama Large Millimeter/submillimeter Array, ALMA, was recently completed by NSF and its international partners.

[Slide.]

You see before you the recent ALMA image of the star HL Tau 450 light-years away, which shows rings of gas and dust circling the star. The gaps in those rings indicated by the dashed lines are swept out by planets just as Saturn satellites sweep out gaps in its famous ring system.

NSF and NASA are collaborating on a new instrument to measure the velocities of stars precisely and detect motions influenced by planets having masses similar to Earth's. This instrument will be installed on the university- and NSF-supported wind telescope in 2018. Finding and characterizing Earth-like planets is an important step in understanding how planetary systems form and evolve and ultimately whether they can host life.

NSF and its awardees also are constructing two major observatories recommended by decadal surveys and funded by Congress. The Daniel K. Inouye Solar Telescope, which you see before you—that's an actual image, not an artist's conception—is being built on the island of Maui. Its observations will provide a deeper understanding of the sun's processes. Those processes lead to the activity that we call space weather, which has the potential to significantly impact communication and navigation systems in space and on the ground, power grids, and astronaut safety.

NSF, with DOE and private partners, leads the construction of the Large Synoptic Survey Telescope, LSST. LSST is the highest priority ground-based recommendation of the last decadal survey, and it will revolutionize modern astrophysics. LSST will discover thousands of potentially hazardous near-Earth asteroids. It will enable contributions by citizen scientists who will use its data sets to participate in the excitement of astronomical discovery.

NSF has also responded to another decadal survey recommendation by initiating a midscale innovations program. This initiative is an ideal hands-on training ground for young scientists and instrument-builders who will participate in the great observatories of the future.

When I left graduate school, we did not know that the expansion of the universe was accelerating, that there were thousands of other solar systems, or that we would detect gravitational waves from merging black holes. Those discoveries relied on many years of support for individual investigators on spectacular computer simulations and on frontier observatories.

With NSF observatories such as ALMA, the Laser Interferometer Gravitational-Wave Observatory, and the IceCube Neutrino Observatory, we are moving rapidly into an era of multi-messenger astrophysics. NSF is proud to work with our many partners and the broad community of scientists. We are poised to continue a journey of discovery on behalf of the American public, and we thank you and all U.S. taxpayers for your support.

This concludes my testimony and I'd be happy to answer any questions.

[The prepared statement of Dr. Ulvestad follows:]



Testimony of

**Dr. James S. Ulvestad
Division Director
Division of Astronomical Sciences
National Science Foundation**

Before the

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

Hearing

On

Astronomy, Astrophysics, and Astrobiology

July 12, 2016

Chairman Babin and Ranking Member Edwards, Chairwoman Comstock and Ranking Member Lipinski, and Members of the Subcommittees. I sincerely thank you for holding this hearing and for the opportunity for the National Science Foundation (NSF) and its partners to discuss the exciting recent progress in astronomy and astrophysics, and the outlook for the future. We are all excited by the remarkable science in exoplanets, studies of dark energy, and the evolution of the universe. But I also would like to step back and highlight the historical context, namely that the remarkable progress we see in astrophysics is the product of multiple National Academies' decadal surveys, and the sustained long-term effort of the basic research community.

The Context: A Special Moment

We have come to a special moment in viewing the universe. Theoretical, experimental, and technological advances have opened new windows on the cosmos. For millennia, humans viewed light from the sky to learn about the universe. Four hundred years ago, Galileo brought new technology to bear, and the opportunities have exploded. Today we observe across the electromagnetic spectrum from radio waves to gamma rays, and now we are ready to look in fundamentally different ways with a powerful collection of

approaches. Just as electromagnetic radiation gives us one view, particles such as neutrinos and cosmic rays provide a different view, and gravitational waves give yet another. In this new era of multi-messenger astrophysics, NSF has a leadership role.

The Impact of Decadal Surveys

In the 1950s, the same decade when NSF was formed, NSF established national observatories for the benefit of the entire U.S. astronomical community. The philosophy behind the formation of these national observatories was the same as that of NSF—their telescopes were open to use by all scientists, without regard to their home institution, purely on the basis of the quality of their scientific proposals. The national telescopes were built and operated not for the sake of having large facilities, but to enable scientific research requiring tools that only the federal government can deliver.

Within a few years, the U.S. astronomy community carried out a priority-setting exercise, the first of what became a series of surveys of the field carried out approximately every 10 years. The sixth of these studies, now known as decadal surveys, was delivered in 2010 by the National Academies. The decadal surveys include both the space-based astronomy supported by NASA and the ground-based astronomy enabled by NSF; in 2010, the Department of Energy (DOE) participated as well. Most young astronomers today have used data from both space- and ground-based telescopes, either to observe fundamental phenomena or to construct theoretical predictions that may be testable by those observations. Hence, the cooperation of agencies in sponsorship of the decadal surveys is critically important to delivering the best science return for our taxpayer dollars.

What is a decadal survey? An enduring purpose of decadal surveys is to survey the state of astrophysics, identify the most important science goals for the upcoming decade, and recommend a program to the federal agencies that best addresses those science goals. These surveys are carried out by the community of scientists, not by the federal agencies. Thus the decadal survey recommendations are truly the outcome of broad-based merit review. Their impact reaches beyond the federal government; university and foundation investments also are driven by the same community-derived science questions.

For 50 years, the decadal surveys have driven the evolution of federal observatories. The 1970 decadal survey recommended the Very Large Array radio telescope, while the 1990 decadal survey recommended the large optical/infrared telescopes that became the International Gemini Observatory. The 1990 survey also recommended the Millimeter Array, completed within budget in 2013 as the international Atacama Large Millimeter/submillimeter Array (ALMA). Thus NSF's frontier astronomical observatories have grown and evolved based primarily on the recommendations of the community-based surveys.

Fundamentally, the decadal surveys recommend the most important science, and the observatories that they recommend have reaches expanding across multiple decades. Although the large observatories may be the most visible components of decadal surveys,

the true driving force is the science that is carried out by thousands of researchers at hundreds of U.S. institutions, from senior faculty to undergraduate and even high school students. Recent decadal surveys have paid close attention to the balance between the funding of the spectacular scientific tools and the support of the individual researchers who use the tools to deliver frontier science. These researchers often achieve results that could not be guaranteed when the tools were first envisioned. For example, the scientific reach of the Laser Interferometer Gravitational-wave Observatory, LIGO, was greatly extended by the development of computer simulations funded by dozens of individual investigator awards over the last thirty years. Hence the first detections of gravitational waves were not just detections, but were accompanied by an understanding of the masses and even the spins of merging black holes more than a billion light years away.

New Worlds, New Horizons in Astronomy and Astrophysics: the 2010 Decadal Survey

This historical tour now brings us to the most recent decadal survey, delivered to the federal agencies in August 2010. That survey identified three principal science areas of focus for the present decade. They are:

- (1) Cosmic Dawn: Searching for the First Stars, Galaxies, and Black Holes;
- (2) New Worlds: Seeking Nearby Habitable Planets; and
- (3) Physics of the Universe: Understanding Scientific Principles.

Not surprisingly, these scientific areas are not newly identified for this decade, but represent enduring human quests. Spectacular advances are being made using new observational tools recommended in previous decades, as well as those to be built in the future.

Take “New Worlds” as an example. The first half of this decade has seen amazing discoveries from both ground- and space-based observatories. ALMA has imaged the disks of dust and gas orbiting newly forming stars, including gaps that are surely swept out by newly forming planets. Both the Gemini Observatory and privately funded telescopes such as the Keck Observatory have imaged planets orbiting other stars. NASA’s Kepler Space Telescope has detected thousands of exoplanets, but it is ground-based telescopes that measure the subtle variations in stellar velocities that reveal the masses of the planets. At present, NSF and NASA are collaborating on construction and implementation of a new instrument to measure these velocities very precisely; it will be installed on the WIYN telescope that is funded and operated collaboratively by several universities and NSF’s National Optical Astronomy Observatory. These are all basic and important steps toward understanding how planetary systems form and evolve, and ultimately the likelihood that they host life.

Because decadal surveys are aspirational, their expansive visions inevitably are constrained by economic realities. But NSF takes very seriously the priorities set by the decadal surveys, and makes every effort to fund the most important recommendations provided by the community.

At present, NSF and its awardees are constructing two major astronomical observatories recommended by decadal surveys and funded by Congress through the NSF Major Research Equipment and Facilities Construction account. We are building the Daniel K. Inouye Solar Telescope (DKIST) atop Haleakala on the island of Maui. The 2000 decadal survey recommended this telescope, and it is on schedule for completion by early 2020. Its observations of magnetic phenomena and energy transport in the Sun will be critical to the understanding of the ultimate source of space weather, which has a dramatic impact on our technological society.

NSF is leading construction of the Large Synoptic Survey Telescope, LSST, the highest priority ground-based recommendation of the 2010 decadal survey. LSST is on schedule to begin its 10-year survey by late 2022. LSST construction results from a strong NSF collaboration with the DOE and private funding partners, while its operations also will include substantial international contributions. LSST will revolutionize many areas of modern astrophysics, with its defining science cases including a survey of the contents of the solar system, and a robust investigation of the nature and evolution of the mysterious “dark energy” that is accelerating the expansion of the universe. LSST will discover thousands of Near-Earth Asteroids. With its well-characterized data sets, LSST is well-positioned for contributions by citizen scientists, and part of the construction plan is the development of a public interface to the datasets. Thus citizens with a variety of backgrounds and capabilities will participate in the excitement of astronomical discovery.

Two important recommendations of the 2010 decadal survey were the initiation of a Mid-Scale Innovations Program, known as MSIP, and increases in the NSF’s individual-investigator programs. NSF initiated MSIP, which targets programs that are too large for individual investigators, but can provide discoveries on timescales much shorter than the major observatories. MSIP is an ideal, hands-on training ground for young scientists and instrument builders who will go on to participate in the great observatories of the future. For example, the first round of this program funded the Zwicky Transient Facility, expected to make important discoveries in time-domain science and set the stage for the millions of transient sources that LSST will discover each night.

Where Are We Going?

Let me recap the tremendous progress in astrophysics over the past several decades. When I left graduate school in 1981, we did not know that the expansion of the universe was accelerating, nor that there were planets beyond our solar system, nor that we would be able to detect gravitational waves from merging black holes. The unpredicted discovery of the acceleration of the universe in the 1990s relied on many years of individual investigator awards, NSF and privately funded observatories, and NASA missions. Progress in understanding the early universe now relies on mid-sized experiments with crucial contributions from graduate students and postdocs. Understanding the observations is enabled by spectacular simulations and visualizations by individual investigators who take advantage of large national computational facilities. The discovery and fundamental understanding of exoplanet populations and formation

needs large observatories such as the Kepler Space Telescope and ALMA, but also needs the growing population of individual researchers who make observations, analyze the data, and interpret the surprising discoveries we are now making.

With observatories such as ALMA, LIGO, and the Ice Cube Neutrino Observatory, NSF and its community are moving rapidly into an era of multi-messenger astrophysics. We at NSF are proud to work with our federal partners at NASA and DOE, as well as our non-federal partners, and most importantly with the broad community of scientists. We are poised to continue our journey of discovery on behalf of the American public, and we thank you and all U.S. taxpayers for your support.

This concludes my testimony, and I would be happy to answer any questions.

James S. Ulvestad

Dr. James S. Ulvestad is the Division Director of the Division of Astronomical Sciences in the Directorate for Mathematical and Physical Sciences at the National Science Foundation, a position he has held since 2010. He leads a staff of 25 and oversees an annual budget of \$246 million, plus major observatory construction projects with an additional budget of \$100 million in FY 2016. Dr. Ulvestad earned a Bachelor's degree in astronomy from the University of California at Los Angeles and a Ph.D. degree in astronomy from the University of Maryland. He was previously an Assistant Director of the National Radio Astronomy Observatory (NRAO), where he was in charge of the Very Large Array and Very Long Baseline Array radio telescopes, and later was the head of the NRAO New Initiatives Office. Before his time at NRAO, Dr. Ulvestad served in various capacities at the NASA Jet Propulsion Laboratory, where he played important roles in several interagency and international programs. Among his community service activities, Dr. Ulvestad chaired the Demographics Study Group of the 2010 National Academies decadal survey in astronomy and astrophysics, was an elected member of the American Astronomical Society Council, and has been a member of NASA's Structure and Evolution of the Universe Subcommittee. He is an author or co-author of more than

Chairman BABIN. Thank you very, very much.
And now, I recognize Dr. Olinto for five minutes to present her testimony.

**TESTIMONY OF DR. ANGELA OLINTO, CHAIR,
ASTRONOMY AND ASTROPHYSICS
ADVISORY COMMITTEE (AAAC),
AND HOMER J. LIVINGSTON PROFESSOR,
DEPARTMENT OF ASTRONOMY AND ASTROPHYSICS,
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Dr. OLINTO. Thank you, Mr. Chairman.

Chairman Babin, Chairwoman Comstock, Ranking Member Edwards, Ranking Member Lipinski, Members of the Subcommittee, and Chairman Smith, thank you so much for having us come here today and it's a pleasure for me to share findings of the Astronomy and Astrophysics Advisory Committee. I'm Angela Olinto, professor of astronomy and astrophysics at the University of Chicago and the current Chair of the AAAC, which is a FACA committee of 13 scientists charged to assess the coordination of astronomy and astrophysics programs of the NSF, NASA, and the DOE. And also we assess the status of the activities relating to the priorities of the decadal surveys of the National Academies.

Over the last few decades, astronomers and astrophysics have revolutionized our understanding of the universe, our place in it, and the fundamental laws that govern its evolution and the systems within it. These impressive achievements are a direct result from the long-standing national investment in basic scientific research. I thank the Committee and its role and continuing support for basic science.

This year, the world celebrated the historic breakthrough of the first observations of gravitational waves by LIGO. This landmark discovery discussed here in February demonstrates the power of long-term investment in basic research by the United States through the NSF and the ability of scientists worldwide to work together in the challenging and fascinating quest to understand nature.

This new window enables direct observations of the most extreme events of our universe including the earliest moments of the Big Bang. Primordial gravitational waves may soon be discovered by the studies of cosmic microwave backgrounds, while a future gravitational wave space mission reached an important milestone this year, the success of the LISA Pathfinder.

Gravitational waves add a new dimension to traditional astronomy, which is based on the broad electromagnetic spectrum. Together with cosmic rays and neutrinos the multi-messenger universe is now observed with frequencies spanning 35 orders of magnitude. If we translate that to music, it is equivalent to a piano with 116 octaves instead of the usual seven, which would be 83 foot piano, twice the size of this room. We need a lot of hands and bright minds to play such an instrument.

Astronomy and astrophysics contributes to astrobiology in many areas, most prominently in the study of new worlds or exoplanets, one of the three main science things of the 2010 decadal survey.

The diversity of the discovered new worlds have surprised us all. They are much more numerous and diverse than the most creative science fiction imagined.

An active program to characterize exoplanets, their services and atmospheres, uses both ground and space telescopes. The launch of JWST and TESS in the next two years will strengthen the effort further. JWST, the most powerful telescope, as mentioned here before, will be taking spectra of transiting exoplanets, while TESS will be searching for nearby Earth-like planets, providing great targets for JWST.

In the next decade, the highest decadal priority, WFIRST, will inaugurate space-based direct imaging and reflected light and pave the way to a future flagship mission that might image Earth-like planets.

The AAAC finds the U.S. investment in astronomy and astrophysics continues to support an outstanding portfolio of preeminent research facilities and the coordination between NSF, NASA, and DOE has been exemplary. These discoveries have captivated the public and inspired new generations of scientists and engineers to continue to expand our knowledge and secure our future leadership in science, technology, and space.

However, the AAAC is concerned about the balance of the portfolio. At both NSF and NASA, competed grants and midscale programs are being squeezed by flat or declining budgets. These programs form the new generation of scientists and ideas. Success rates have declined in the last decade from 30 percent to 20 percent, and this is affecting the morale of the community. As we plan for a future with the U.S. leadership, investment in the next generation of scientists and ideas is crucial.

I was born in the United States because my father came here to do his Ph.D. before returning to Brazil. Twenty years later, I dreamed of doing the same thing. I applied to U.S. graduate schools in spite of being bed-bound. I was very lucky because I have my health back and also the opportunity given to my generation by those who built the great U.S. research institutions in the past.

Since then, I have mentored many students at Chicago who are now following their dreams in academia, national labs, and industry. Of my graduate students, 73 percent have been women, including the first African-American to get a Ph.D. in our department. I would like to ensure that the diverse and brilliant young talent in this country will also have the great opportunities we have.

My one message today is to strengthen the base program that needs help after the past years of constrained budgets. Let's support the next generation as past generations have supported us. Thank you for listening. I'll be pleased to answer any questions.

[The prepared statement of Dr. Olinto follows:]

Statement of

Dr. Angela V. Olinto

Homer J. Livingston Distinguished Service Professor of Astronomy & Astrophysics,
 Kavli Institute for Cosmological Physics, Enrico Fermi Institute
 The University of Chicago
 Chair of Astronomy and Astrophysics Advisory Committee

before the

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

On

Astronomy, Astrophysics, and Astrobiology
 July 12, 2016

Chairman Babin, Ranking Member Edwards, Chairwoman Comstock, Ranking Member Lipinski, and Members of the Subcommittees, it is my privilege to share with you the recent findings of the Astronomy and Astrophysics Advisory Committee (AAAC).

I am Angela V. Olinto, Professor of Astronomy & Astrophysics at the University of Chicago, and current Chair of the AAAC. The AAAC is a Federal Advisory Committee Act (FACA) committee established under the National Science Foundation (NSF) Authorization Act of 2002 and amended by the Department of Energy (DOE) High-End Computing Revitalization Act of 2004.¹ This thirteen member committee of leading US astronomers and astrophysicists is charged to assess and make recommendations regarding the coordination of astronomy and astrophysics programs of the NSF, the National Aeronautics and Space Administration (NASA), and the DOE; and the status of the activities relative to the priorities of the 2010 National Research Council (NRC)² decadal survey *New Worlds, New Horizons in Astronomy and Astrophysics (NWNH)*³ and its predecessors. I have served as a member of the AAAC from 2003 to 2006 and again starting in 2013.

Astronomical Progress in Astronomy and Astrophysics

Over the last few decades, astronomers and astrophysicists have revolutionized our understanding of the universe, our place in it, and the fundamental laws that govern its evolution and the systems it contains. These discoveries have captivated the public and inspired new generations of scientists and engineers to continue to expand our knowledge and secure our future leadership in science, technology,

¹ <http://www.nsf.gov/mps/ast/aaac/charter.pdf>

² The National Academies was the National Research Council in 2010.

³ <http://www.nap.edu/catalog/12951/new-worlds-new-horizons-in-astronomy-and-astrophysics>

and space. These impressive achievements are the direct result of the long-standing national investment in basic scientific research in the US.

This year the world witnessed the historic breakthrough of the first observations of gravitational waves by the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO). Announced on February 11th, this discovery crowned the century-old effort to understand Gravity, the most challenging force to master. The observed signal confirmed the predictions of Einstein's general relativity and opened a new window onto the universe. The recently reported second LIGO event hails the new era of observations that will transform our view of the universe. This momentous discovery demonstrates the power of long-term investment in basic research by the US through the NSF and the ability of scientists worldwide to work together in the challenging and fascinating quest to understand nature.

The new gravitational wave window enables more direct observations of the most extreme events in our universe, including the earliest moments of the Big Bang. This new window adds a completely new dimension to traditional observational astronomy, which is based on the broad electromagnetic wave spectrum. Electromagnetic waves currently provide the bulk of our knowledge, from the earliest moments of the universe to planetary systems in our neighborhood of the Galaxy.

Combined space and ground-based astronomical observatories have recently shown that the universe is not only expanding but its expansion is accelerating due to a yet to be explained dark energy component, and that most of the matter in the universe is not normal matter, but dark matter. In addition, led by the NASA Kepler mission, space- and ground-based observatories have revealed a plethora of planetary systems harbored by the hundreds of billions of stars in our Milky Way galaxy, motivating the ongoing search for Earth-like habitable planets.

Adding to electromagnetic and gravitational wave observations, measurements of cosmic rays and neutrinos have also blossomed in the last few years with the recently opened window of high-energy astrophysical neutrinos by the NSF-funded IceCube observatory at the South Pole. Together, these three types of observations — light waves, gravitational waves, and cosmic rays and neutrinos — today cover 35 orders of magnitude in frequency, forming the broad palette of Multi-Messenger Astronomy and Astrophysics.

Coordination of Astronomy and Astrophysics Programs

As summarized in the annual AAAC reports, US investment in astronomy and astrophysics continues to support an outstanding portfolio of preeminent research facilities and the coordination between the NSF, NASA, and DOE has been exemplary.

As outlined in the 2013 AAAC report⁴, "programmatic partnerships among agencies or involving other entities are appropriate when they deliver increased science capability, cost effectiveness, access to specialized expertise and avoidance of duplication." The same report lists dozens of notable cases of joint agency efforts that have successfully followed these guidelines. The 2014 AAAC report⁵ laid down the AAAC Principles for Access,⁶ based on the best science, open access, and reciprocity, for current and

⁴ http://www.nsf.gov/mps/ast/aaac/reports/annual/aaac_2013_130308finalreport.pdf

⁵ http://www.nsf.gov/mps/ast/aaac/reports/annual/aaac_2014_report.pdf

⁶ http://www.nsf.gov/mps/ast/aaac/aaac_2014_principles_for_access-v2.pdf

future partnerships among the three agencies assessed by the AAAC and with other partners including private and international entities.

Most of the major science programs recommended by decadal surveys require coordinated and complementary efforts in multi-facility astronomical observations, simulations, theory, and analysis. For example, remarkable results from the Hubble Space Telescope routinely include complementary observations from other space telescopes and ground-based larger aperture optical to radio telescopes, as well as coordinated work on theory and simulations needed to interpret the observations.

Recent outstanding results from well-coordinated projects include the discovery of 17 new Milky Way dwarf satellites by the Dark Energy Survey (DES), a project jointly supported by NSF and DOE. These Milky Way satellites are ideal targets for indirect dark matter searches, which are led by the Large Area Telescope instrument aboard the NASA Fermi Gamma-ray Space Telescope, a partnership between NASA and DOE.

A similar NSF and DOE partnership is now in place to achieve the first large-scale priority of the *NWNI* decadal survey on the ground, the Large Synoptic Survey Telescope (LSST). LSST is a multipurpose, wide-field, optical survey telescope targeting aspects of all three *NWNI* science themes; the cosmic dawn; new worlds; and the physics of the universe. LSST is now under construction and should start its main operations in 2022.

During the past year, the number of exoplanet candidates detected by the NASA Kepler and K2 missions surpassed four thousand, vastly expanding our understanding of planets and nurturing the public's spirit of adventure and discovery. (Exoplanet stands for an extra-solar planet or a planet that orbits a star other than the Sun.) Among those candidates, about a dozen are small enough to be rocky and orbit within the Habitable zone of their host stars, where they receive similar stellar radiation to that received by the Earth from the Sun. Among these exoplanets are ones that orbit and transit nearby stars, which scientists can study in more detail with ground and other space-based telescopes. Adding to the exoplanet population studies are observations of the early stages of planet formation by the NSF-funded Atacama Large Millimeter/submillimeter Array (ALMA), which was a top priority from previous decadal surveys and began full operations in 2013.

Addressing the *NWNI* priority of high-precision radial velocity surveys of nearby stars in order to validate and characterize exoplanet candidates and amplify the science impact of the Transiting Exoplanet Survey Satellite (TESS) mission, NASA and NSF recently partnered on the Extreme Precision Doppler Spectrometer (EPDS) instrument funded by NASA to be placed on the WIYN telescope at Kitt Peak National Observatory (KPNO), part of the National Optical Astronomy Observatory (NOAO) funded by NSF.

Another important example of inter-agency cooperation is the study of the earliest moments of the universe with cosmic microwave background (CMB) observations. The search for primordial gravitational waves through the observation of special patterns in the CMB polarization maps (named B-modes) has now reached a third generation of experiments with sensitivity to make this ground-breaking discovery. CMB scientists funded by NSF, DOE, and NASA are planning for a future (Stage-4) ground-based CMB effort, known as CMB-S4, to improve the sensitivity to CMB B-modes by orders of magnitude. The ground-based CMB-S4 effort will complement NASA experiments from balloons and space. On sub-orbital efforts, NASA just demonstrated the new, cutting-edge, super-pressure balloon

capability flying the first science payload, the Compton Spectrometer and Imager (COSI), out of Wanaka, New Zealand, for a record 46-day mid-latitude flight.

Status of Decadal Survey Priorities

The AAAC charter directs the committee to assess and advise on the progress of the three funding agencies (NSF, NASA and DOE) on the recommendations made by the astronomy and astrophysics Decadal Surveys from the National Academies. The most recent survey report, *New Worlds, New Horizons in Astronomy and Astrophysics (NWNH)* from 2010, was the first to include the DOE. *NWNH* will soon be supplemented by a report from the *Midterm Astronomy and Astrophysics Assessment* committee convened by the National Academies at the request of the agencies. Implementation of *NWNH* is also closely related to other planning exercises, including the Cosmic Frontier recommendations in the Particle Physics Project Prioritization Panel (P5) report (which addresses DOE High Energy Physics and the NSF Directorate for Mathematical and Physical Sciences), the NSF Division of Astronomical Sciences (AST) Portfolio Review, and NASA Astrophysics Division (APD) Senior Reviews.

The 2016 AAAC report⁷ highlights the excellent progress by the agencies toward the construction of the highest priorities in the most recent decadal surveys. The highest priority of the 2001 *Astronomy and Astrophysics in the New Millennium*⁸ decadal survey, the James Webb Space Telescope (JWST), is on track for its planned October 2018 launch date, thanks to the continued support by Congress.

JWST will be the most powerful telescope ever launched into space. Its four science instruments will operate in the near- and mid-infrared, where light is better able to penetrate regions of gas and dust and is well-suited to the study of highly redshifted stars and galaxies in the early Universe. JWST will provide incisive spectroscopy of transiting exoplanets with properties approaching those of the Earth. On the 4th of February 2016, NASA announced that the full 18-segment primary mirror was completed marking a major milestone for the project. The primary optical system will be integrated with the other telescope components for testing of the observatory at Johnson Space Center in 2016 and 2017.

The highest 2010 *NWNH* large-scale priority in space, the Wide-Field Infrared Survey Telescope (WFIRST), is also progressing well, having moved into formulation phase (Phase A) in February 2016 under strong NASA stewardship of science and project teams. WFIRST is the next-generation, large space observatory designed to perform wide-field imaging and spectroscopic surveys of the near infrared sky. WFIRST will contribute to all three *NWNH* science themes, by answering essential questions about dark energy, exoplanets, and galaxy evolution.

The AAAC commends NASA for adapting to the availability of the Astrophysics Focused Telescope Assets (AFTA) 2.4-meter mirrors, proceeding with mission concept development, and assembling the formulation science teams to enable the start of formulation for this highest-ranked, large space project in *NWNH* by mid-decade. The addition of a coronagraph to WFIRST will augment the exoplanet capabilities of the mission. WFIRST will be able to inaugurate space-based direct imaging in reflected light to pave the way towards the imaging of Earth-like planets in a future flagship mission.

⁷ http://www.nsf.gov/mps/ast/aaac/reports/annual/AAAC_2015-16_Report.pdf

⁸ <http://www.nap.edu/catalog/9839/astronomy-and-astrophysics-in-the-new-millennium>

The next *NWNNH* priorities for large projects in space are, in order of priority, the augmentation of the Explorer Program, the Laser Interferometer Space Antenna (LISA), and the International X-ray Observatory (IXO). The Explorer Program provides frequent flight opportunities for innovative, streamlined space investigations within the astrophysics and heliophysics science areas. The next Astrophysics Explorers are the mission of opportunity (MOO) Neutron star Interior Composition ExploreR (NICER) currently planned for deployment at the International Space Station in 2017, and the Medium-class Explorer (MIDEX), the Transiting Exoplanet Survey Satellite (TESS), with a launch currently planned for August 2017. TESS will search for candidate Earth-like transiting planets orbiting bright stars close to the sun to provide targets for JWST to follow. A recent Small Explorer (SMEX) announcement of opportunity call led to concept studies of five candidate SMEXs and MOOs. A MIDEX announcement of Opportunity call is planned for later in 2016.

Given budgetary constraints on the ability of NASA to respond to the full *NWNNH* program, NASA has partnered with the European Space Agency (ESA) on ESA's second and third large missions (L2 and L3) to respond to the 3rd (LISA) and 4th (IXO) *NWNNH* priorities in space. LISA is a low-frequency gravitational wave observatory proposed to complement higher-frequency Earth-based observatories like LIGO and to provide access to new means of studying black holes and making precision tests of general relativity. A technology mission, LISA Pathfinder, led by ESA with NASA partnership, was successfully launched on December 3, 2015. It achieved the lowest acceleration motion ever and tested new sensing technology needed for LISA. The AAAC encourages NASA to continue on its plans to partner with ESA on its L3 gravitational wave observatory mission, which has a tentative launch date of 2034.

IXO is a next-generation X-ray observatory for studies of the high-energy Universe. In 2014, ESA selected a re-scoped X-ray mission, called Advanced Telescope for High Energy Astrophysics (ATHENA), with launch planned for 2028. NASA is working towards US participation in the ESA ATHENA project, providing future access to X-ray resources for the US astronomy and astrophysics community.

As mentioned above, the highest *NWNNH* priority for large projects on the ground is LSST, which is progressing well, with a strong NSF and DOE partnership for construction and operations. The second highest priority is the NSF Midscale Innovations Program (MSIP), a competed grants program for mid-scale projects, designed to allow significant advances in scientific discovery beyond the scope of the Astronomy and Astrophysics Grants (AAG) program. Following MSIP in priorities is the Giant Segmented Mirror Telescope (GSMT), a very large, ground-based optical and near-infrared telescope that can provide a spectroscopic complement to the JWST, ALMA, and LSST. Two international consortia led by US institutions are planning GSMT construction: the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT). Finally, the fourth *NWNNH* priority for ground-based astronomy is the Atmospheric Čerenkov Telescope Array (ACTA), an international instrument for high-energy gamma-ray astrophysics. Budgetary constraints have not allowed progress on recommendations for a Federal partnership in GSMT nor in ACTA.

The AAAC finds that given the constrained budget realities, the NSF MSIP program is funded at a level well below that envisioned in *NWNNH*. In addition, MSIP is becoming the only mechanism available for funding other priority activities advocated in *NWNNH*. NSF/AST is funding MSIP at the highest level commensurate with its program balance. However, the program is supporting a larger number of projects with a lower budget than recommended in *NWNNH* and is not able to support the higher-cost projects as envisioned by *NWNNH*.

In its efforts to follow the recommendations of *NWNH*, NSF/AST initiated a portfolio review process that outlined a plan for divestment of some existing facilities to enable NSF to meet the scientific priorities of *NWNH*. The AAAC commends NSF/AST for finding creative solutions to respond to the recommendations made by the Portfolio Review Committee (PRC). These actions will reduce the amount that NSF/AST will spend on the operating budgets of lower-priority facilities and thus enable the NSF to move closer to the desired balance in the portfolio recommended by *NWNH*. The AAAC recommends that strong efforts by NSF for facility divestment continue as fast as is practical.

Competed Grant Success Rates in US Astronomy and Astrophysics

The last decade has witnessed the construction and operations of world-leading observatories with the potential to secure the long-term leadership of US astronomy and astrophysics. Over the same period funds available for community-wide openly competed grants have remained largely flat in both NSF/AST and NASA/APD. Balance between funding construction and operations of observatories and maintaining a healthy core program of competed grants is crucial for the future of the field. As emphasized in *NWNH* page 4, “Maintaining a balanced program is an overriding priority for attaining the overall science objectives that are at the core of the program recommended by the survey committee.”

An unfortunate consequence of the budgetary pressure on the portfolio is the decline of success rates in competed grants as discussed in the AAAC report *Competed Grant Success Rates in US Astronomy and Astrophysics*.⁹ From 2004 to 2014, the success rates in the NSF/AST AAG program declined from 30% to 17% and NASA Astrophysics Research and Analysis (R&A) proposal success declined from 30% to about 20%. During the same period no significant changes occurred in the distribution of proposal merit. Declining success rates have affected highly rated proposals, which may cause a loss in momentum for the field as a new generation gets discouraged and new discoveries are missed.

The AAAC reports tell a story of impressive accomplishments by agencies and scientists in the context of the challenging budget environment of the past few years. The AAAC recommends that NSF and NASA continue their challenging work toward balance of the portfolio and believe that a modest increase in investment in the base program is warranted to help alleviate the proposal pressure crisis, and better realize the scientific potential of the leading facilities and missions.

Concluding Remarks

The AAAC is very grateful to the continued support of Congress for basic research in general and astronomy and astrophysics in particular. With the sustaining support from Congress, the well coordinated efforts of the agencies, and the enduring tradition of the community to prioritize its aspirations through the decadal survey process, US astronomy and astrophysics will continue to lead the world in our quest to understand the universe, its laws, origins, and future, and our own origins and future. The astonishing discoveries that we can now only imagine will continue to captivate the public and inspire future generations to study scientific and technical fields that will further enrich the prosperity of this great Nation.

Thank you for listening, I will be pleased to answer any questions you may have.

⁹ http://www.nsf.gov/mps/ast/aaac/reports/annual/AAAC_2015-16_Report.pdf

Dr. Angela V. Olinto

*Homer J. Livingston Distinguished Service Professor
 Department of Astronomy and Astrophysics;
 Kavli Institute for Cosmological Physics,
 Enrico Fermi Institute; and the College; and
 Chair of the Department of Astronomy and Astrophysics;
 The University of Chicago*

Olinto received her B.S. in Physics from the Pontificia Universidade Católica (PUC) of Rio de Janeiro, Brazil in 1981, and her Ph.D. in Physics from the Massachusetts Institute of Technology (MIT) in 1987. She was a postdoctoral fellow at the Fermi National Accelerator Laboratory (Fermilab) in Illinois and subsequently became a faculty member in the Department of Astronomy and Astrophysics, the Kavli Institute for Cosmological Physics, and the Enrico Fermi Institute, at the University of Chicago.

Now the Homer J. Livingston Distinguished Service Professor in Astronomy and Astrophysics, Olinto is the PI of the EUSO-SPB mission and a member of the international collaboration of the Pierre Auger Observatory, both designed to discover the origin of the highest energy cosmic rays. She made significant contributions to the study of the structure of neutron stars, inflationary theory, cosmic magnetic fields, the nature of the dark matter, and the origin of the highest energy cosmic particles: cosmic rays, gamma-rays, and neutrinos.

Olinto served as Chair of the Department of Astronomy and Astrophysics from 2003 to 2006 and is now in her third term. She is a fellow of the American Association for the Advancement of Science, the American Physical Society, and has served on many advisory committees for the National Academy of Sciences, Department of Energy, National Science Foundation, and the National Aeronautics and Space Administration.

She received the Chaire d'Excellence Award of the French Agence Nationale de Recherche in 2006, the Llewellyn John and Harriet Manchester Quantrell Award for Excellence in Undergraduate Teaching in 2011, and the Faculty Award for Excellence in Graduate Teaching in 2015 at the University of Chicago.

Chairman BABIN. [Speaking foreign language.]

Dr. OLINTO. [Speaking foreign language.]

Chairman BABIN. Thank you for that.

I now recognize Dr. Wright for five minutes to present her testimony.

**TESTIMONY OF DR. SHELLY WRIGHT,
ASSISTANT PROFESSOR,
UNIVERSITY OF CALIFORNIA,
SAN DIEGO, CENTER FOR ASTROPHYSICS
AND SPACE SCIENCES,
BREAKTHROUGH LISTEN ADVISORY COMMITTEE**

Dr. WRIGHT. Thank you, Chairman, and esteemed Committee. Thank you for the opportunity to discuss the scientific pursuit for finding other intelligent life in the universe.

I'm an assistant professor in physics at the University of California San Diego. I spend my time teaching astrophysics, researching galaxies, and building new instruments for the world's largest telescopes. I am also one of a few SETI researchers worldwide.

The search for extraterrestrial intelligence, SETI, is a scientific pursuit of detecting technological transmissions from other intelligent life in the universe. In particular, SETI searches for a signal purposely sent or accidentally leaked from an advanced civilization.

We are in the midst of a dramatic paradigm shift. Only in the last few years, thanks to NASA's successful Kepler mission, we know that one in every five sun-like stars in our galaxy harbors an Earth-like planet. This greatly encourages our search for life and intelligent life elsewhere in the universe, but given the lack of sustained academic funds for SETI, few opportunities exist for researchers and students to engage in this field. Yet many believe there is no single discovery that will more fundamentally change humankind's view of our place in the universe than to discover E.T.

Since the search in 1960, SETI is predominantly conducted at radio wavelengths. Numerous SETI programs have made use of the largest U.S. and international radio telescopes. Still, SETI radio searches have barely scratched the surface for detecting faint interstellar signals. Thanks to constantly improving technology, the coming years still promise new, more sensitive SETI searches.

Breakthrough Listen, a ten-year, \$100 million SETI initiative sparked by philanthropist Yuri Milner began operations just this year in January. Breakthrough Listen is using the Green Bank Telescope in West Virginia, the Parkes radio telescope in Australia to attempt a radio search that is 50 times more sensitive and covers 10 times more sky than all previous SETI searches before.

Just this month, the Chinese have finished final assembly of the world's largest radio dish at 500 meters in diameter. Chinese scientists have slated this dish to be used for very sensitive SETI program, thus adding significant international competition to the SETI field.

The radio regime is just one small portion of the electromagnetic spectrum. It has been suggested for decades that other wavelengths may be just as viable for interstellar communication. The discovery of laser technology opened a new realm and offered several advan-

tages over radio. Lasers can be narrowly beamed, thus transmitting power efficiently, and its beam can be packed with more information per energy used.

Using our laser technology today, humans would have the capability to transmit a signal that would be easily detectable thousands of light-years from Earth encompassing millions and millions of stars. Our group has constructed SETI instruments at Lick and Leuschner Observatories to search for fast-pulsed optical laser signals that have a burst within nanoseconds or shorter period. In parallel, team from Berkeley searches for continuous laser signals using high-resolution spectra from Keck Observatory.

Breakthrough Listen also supports an optical SETI program that seeks laser signals and optical spectra at Lick Observatory, but another promising area for SETI is infrared wavelengths. Infrared detectors have been rapidly improving only recently making an infrared pulse laser SETI search possible. In fact, sending a laser signal in infrared is more advantageous because it's less diminished by interstellar dust and gas.

Our team designed and constructed the first-ever near infrared SETI experiment. This program has been superb for training undergraduate and graduate students and postdocs. Our team and others are now working to design and seek funding for new SETI experiments.

Enthusiasm is ever-increasing for SETI but resources are scarce. A huge disparity exists between the enormous public and scientific interest and whether we are unique in the universe and resources that are actually allocated to SETI research. Since 1977, there has been roughly a flat rate of refereed publications about SETI with a number of worldwide dedicated SETI research levels at a mere two dozen. Even with the much-needed catalyst of funds recently provided by private foundations, leveraging private and public sectors is vital for creating a sustainable and growing community of SETI researchers.

Two decades ago, unknowns about astrobiology and extrasolar planets discouraged government funding for SETI. Today, thanks to successful NASA, NSF, and national supported missions, former concerns about the value SETI research no longer apply. While there's much to learn about the universe, the relevance for advancing SETI is stronger today than ever before in the history of humankind, so thank you for your consideration and listening today.

[The prepared statement of Dr. Wright follows:]

Advancing the Search for Extraterrestrial Intelligence

Statement of

Dr. Shelley Adams Wright
Assistant Professor, University of California, San Diego
Department of Physics
Center for Astrophysics & Space Sciences

before the

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

On

Astronomy, Astrophysics, and Astrobiology

July 12, 2016

Chairman Babin, Ranking Member Edwards, Chairwoman Comstock, Ranking Member Lipinski, and esteemed Members of the Subcommittees, I am honored and pleased to have the opportunity to discuss current and upcoming research endeavors in the search for extraterrestrial intelligence (SETI).

I became involved with SETI research in 2000. As an undergraduate at UC Santa Cruz, I attended the first annual Astrobiology conference held at NASA Ames Research Center. I spent my first conference lunch sitting with a group of premiere SETI researchers. During lunch, these scientists hatched the design for an improved optical SETI experiment. I eagerly joined the collaboration and spent two years assembling and commissioning the instrument, as well as learning essential skills about astronomical instrumentation, engineering, and the science behind SETI. Only years later did I appreciate the uniqueness of this fortunate experience. Given the lack of sustained academic funds for SETI, few opportunities exist worldwide for researchers and students to engage actively in SETI. Yet, many people around the globe believe there is no single discovery which will more fundamentally change humankind's view of our place in the Universe than to discover extraterrestrial intelligence (ETI).

Overview

A decade ago, humanity was only able to speculate on whether Earth-like planets were common in our Galaxy. Primarily due to NASA's successful Kepler Mission, we now know that *one in every five* Sun-like stars in our Galaxy harbors an Earth-like planet. There are roughly one trillion stars per Galaxy, and the Hubble Space Telescope has revealed that there are over 100

trillion galaxies in our observable universe. Given the plentitude of stars (roughly 10^{22}) available to host a terrestrial planet coupled with our own technological advances, the search for other intelligent life seems ever more promising.

We are in the midst of a dramatic paradigm shift. For thousands of years, humans have speculated on the uniqueness of our existence in the Universe. Now in the 21st century, we know that organic molecules are abundant in interstellar space; life on Earth exists in extreme conditions in every nook and cranny; and planets are common among stars. These recent discoveries greatly encourage our search for other life, and for intelligent life elsewhere in the Universe.

The Search for Extraterrestrial Intelligence (SETI) is the scientific pursuit of technological transmissions from other intelligent life in the Universe. In particular, SETI searches for electromagnetic radiation (Figure 1) purposely sent or accidentally leaked from advanced civilizations. Historically, we have based the type of SETI searches we conduct (specifically, which frequencies we examine) on our current communications technology and capabilities. Until recently, radio and microwave wavelengths have dominated how humans have communicated over long distances on Earth and even with our spacecraft.

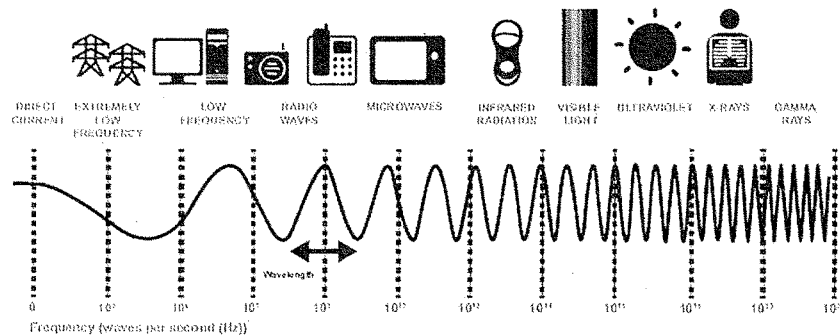


Figure 1: The electromagnetic spectrum and its constituent wavelengths of light. SETI has predominantly been applied at regions of the EM spectrum that humans use for telecommunications. (Photo Credit: ISP review).

Radio SETI

The first SETI experiment commenced over 55 years ago with a radio search by Frank Drake using the National Radio Astronomy Observatory Green Bank Telescope. Radio wavelengths offer distinct advantages for interstellar communication. Generating radio waves is relatively inexpensive because they are low energy, and radio waves can easily traverse through the interstellar medium without being absorbed by intervening dust and gas. However, sizes of the transmitting and receiving antennae must be relatively large (e.g., $\gg 10$ meters) to send and receive distant signals, and the signal frequency needs to be somehow known for the receiver to detect it. In fact, how we communicate with current satellite missions in the Solar System, such

as Juno, is greatly limited by the size and weight of the transmitter and receiver aboard the spacecraft.

Since this initial experiment, SETI has been predominantly conducted at radio wavelengths. Radio searches must make trade-offs between searching for the signal among many frequencies, the sensitivity with which they can detect a signal, and the expanse of sky covered in the search. Usually, if you scan many radio frequencies at great sensitivity, you are limited to a targeted search where you can “listen” to only one star at a time. SETI searches that cover large areas of the sky rather than pointing at a particular star have been conducted, albeit at the price of decreased sensitivity and number of frequencies covered.

Numerous SETI programs have made use of the largest US radio telescopes, the Green Bank Telescope and the Arecibo Observatory. These searches have been complemented by other efforts using international facilities such as the Low Frequency Array in Europe and the Murchison Widefield Array in Australia. Still, SETI radio searches have barely scratched the surface for detecting faint interstellar signals. Our current searches to date have been likened to catching fish in all the worlds’ oceans by gathering a single scoop of water in a pint glass.

Thanks to continual improvements in instrumentation and technology, the coming years promise new SETI radio searches with increased sensitivity at a greater number of frequencies to detect fainter signals with better sky coverage.

Breakthrough Listen, a ten-year \$100 million SETI initiative launched by philanthropist Yuri Milner, began operations in January 2016. This program supports both radio and optical SETI. *Breakthrough Listen* is using the Green Bank Telescope in West Virginia and Parkes Radio Telescope in Australia to simultaneously cover both hemispheres, and conduct a radio SETI search 50 times more sensitive with state-of-the-art electronics and detectors. It will also cover 10 times more sky than previous radio searches. *Breakthrough Listen* supports an optical SETI program that seeks laser signals in the optical wavelength regime using spectra from the Automatic Planet Finder at Lick Observatory (see next section).

Just this month, July 2016, the Chinese have finished final assembly of the world’s largest radio dish that will be competitive with Arecibo Observatory (Figure 2). Construction of the 500-meter dish was completed in 5 ½ years for \$180 million. Chinese scientists have slated this dish to be used for a very sensitive SETI program that promises to be more sensitive than previous SETI searches, thus challenging US leadership in this field.

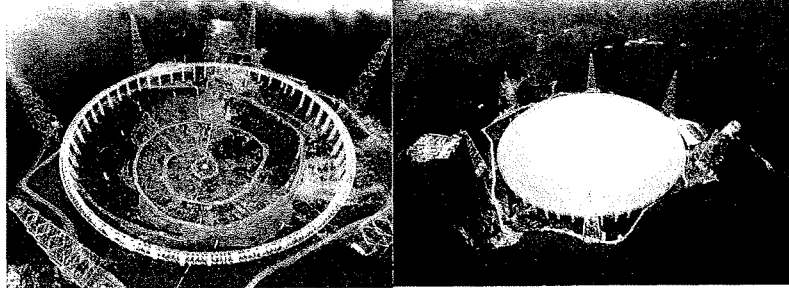


Figure 2: (LEFT) Five-hundred-meter Aperture Spherical Telescope (FAST) under construction in Guizhou Province in 2011. (RIGHT) Completed FAST telescope photographed in July 2016 with all panels installed. FAST operation is scheduled for September 2016, with one of the scientific goals to conduct a sensitive SETI program. (Photo Credit: News.cn).

Optical and Infrared SETI

The radio regime is just one small portion of the electromagnetic spectrum. It has been suggested for decades that there may be more favorable wavelengths at which to conduct our SETI search. Soon after the invention of the laser (or “maser”) in 1959, physicist-inventor Charles Townes suggested that lasers would be one of the best means to communicate on our planet, as well as with spacecraft within the Solar System, and especially across interstellar distances.

The discovery of laser technology opened a new realm of communication, and offered several advantages over radio. Lasers can be narrowly beamed, thus transmitting power efficiently. Additionally, a laser beam can be packed with more information (i.e., energy per bit). Laser communication is an excellent choice for transmission across large distances to a specific target. Laser communication on Earth is advantageous for these same reasons (see Figure 3).

A significant advantage of transmitting lasers across large interstellar distances, particularly at optical and infrared wavelengths, is the ability to generate a signal which outshines a planet’s host star by many orders of magnitude. Lawrence Livermore National Laboratory is capable of generating peak power of a petawatt (10^{15} W) during very short duration laser pulses. Such pulses, when concentrated into a narrow beam by a large telescope, are so powerful that for a brief time they would far outshine *all* of the light from our sun as seen by an extraterrestrial looking our way. Using today’s laser technology, humans have the capability to transmit a signal that would easily be detectable with only meter-class telescopes more than 1,000 light years from Earth, a distance which includes more than a million stars. Realizing this, the SETI community has operated several modest laser SETI programs at optical wavelengths for the last two decades.

These optical searches have focused either on detecting pulsed or continuous laser signals.

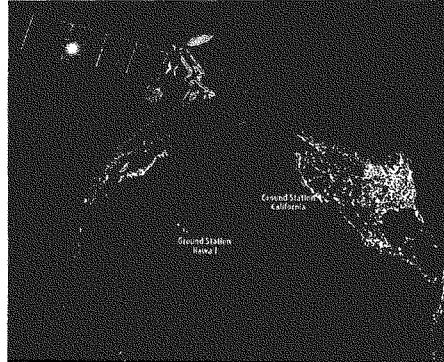


Figure 3: Conceptual drawing of NASA Laser Communications Relay Demonstration (LCRD) mission that uses optical lasers to improve data speeds and bandwidths by a factor 10 compared to traditional radio transmitters. Using lasers across interstellar distances would benefit similarly, with a boost of information per energy sent. (Photo Credit: NASA).

Fast pulsed laser signals (nanosecond or shorter) have the advantage of being distinguishable from other background signals, including terrestrial, atmospheric, and as far as we know, astrophysical phenomena. Although we have no convincing evidence that any natural phenomena will produce a nanosecond or shorter signal at visible or infrared wavelengths, we now have the unique ability to study exotic astrophysical sources like black holes and pulsars in this unexplored frequency and time regime. Such brief pulses would be a particularly distinctive beacon for any civilization wishing to make contact, but *any* such brief signal we detect will be extremely interesting.

On the receiving end, a pulsed optical laser signal has the convenience of being bright even if the frequency of the narrow laser line is not known *a priori*. Constructing an optical SETI experiment is relatively inexpensive compared to radio searches, and can operate on smaller, more economical telescope facilities. Even ground-based gamma-ray telescopes which use fast optical detectors have been cleverly modified to carry out occasional optical SETI searches. A group at Harvard has constructed a dedicated optical SETI experiment to scan large areas of the sky for pulsed laser signals. Our group, in collaboration with Berkeley SETI Research Science Center, has constructed optical SETI instruments at Lick and Leuschner Observatories. Since 2000 we have carried out a targeted search of over 10,000 nearby stars with these instruments. The Lick Observatory instrument was even used for monitoring NASA's Deep Impact satellite slamming into Comet Tempel 1.

In parallel, a team from Berkeley has carried out continuous laser signal searches with the W. M. Keck Observatory using data obtained since 1997. Previous measurements of nearby stars taken with high-resolution optical spectrographs were scanned for any unusual signatures of lasers. Spectrograph searches for a continuous laser signal achieve very high sensitivity and would be able to detect a relatively weak signal, but the required observing time per star is high. An all-sky search with this technique is beyond our reach with current spectrographs, and this type of

search, while entirely worthwhile, is less efficient in covering large areas of the sky than pulsed laser SETI experiments.

Until recently, most laser SETI searches have focused on receivers that could detect optical wavelengths of light, because available detectors were sufficiently advanced and sensitive. However, sending a laser signal in the infrared is advantageous because the light is less diminished by intervening dust and gas. A laser signal propagating in the near-infrared rather than optical ("visible") light through the Galactic plane would be far less diminished, by several orders of magnitude. In addition, infrared suffers less from interference by background light from our galaxy. The telecommunications and defense industries have rapidly improved the performance and sensitivity of infrared detectors, which has only recently made an infrared pulsed laser SETI search possible.

Beginning in 2012, our team has procured uniquely capable state-of-the-art infrared detectors, and designed and constructed the first near-infrared pulsed laser SETI experiment. This instrument was commissioned at Lick Observatory in the spring of 2015 (Figure 4). We are now operating in full campaign mode, targeting a range of nearby stars and unusual astrophysical sources, as well as distant galaxies. Our program excels in training next generation scientists while engaging them in active SETI research. This small and privately funded near-infrared SETI program has already involved three undergraduates, one graduate student, and one postdoctoral fellow. Superb training is offered in general astronomical instrumentation and observations, as well as unique SETI research. This system is the first of its kind and will evolve as newer, more sensitive detectors become available. Although our current campaign is a targeted search there is significant interest to extend this experiment to larger areas of the sky.

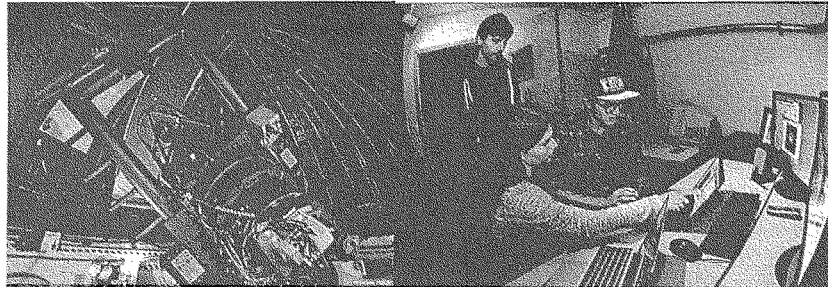


Figure 4: (LEFT) The near-infrared SETI instrument installed at Lick Observatory, California has been in full operation since March 2015. (RIGHT) UC San Diego undergraduate students Melisa Tallis and Andres Duenas discuss results with Dr. Jérôme Maire, Dunlap Postdoctoral Fellow and near-infrared SETI team member. This instrument was constructed and will be used by multiple undergraduate and graduate students. (Photo Credits: Laurie Hatch).

Making use of the latest technological advancements in electronics, computing, and instrumentation is essential for advancing SETI efforts. Our group is now collaborating with Harvard and Berkeley to design both an *all-sky all-the-time* optical pulse SETI system, in addition to a wide field of view infrared pulsed SETI system. These new programs will be

seeking funds to build dedicated telescopes and new instrumentation that will make use of the most advanced detectors. Pulsed laser SETI instruments are relatively cost effective, typically \$0.2-1 million, and will advance SETI in completely new directions.

Concluding Remarks

Humans have been using radio communication for barely over 100 years and laser communication for the last 30 years. This is only a sliver of time compared to the lifetime of human civilization ($> 10,000$ years) and life on our planet (> 3 billion years). Technology available today dictates the types of SETI searches we currently conduct, but many creative SETI programs await to explore other portions of the electromagnetic spectrum. Theoretical astrophysicists contemplate possibilities of communication with neutrinos or even gravity waves. If we hope to answer the question that has intrigued us for centuries (*Are we alone?*), we need the best and brightest scientists creating new methods for SETI.

Enthusiasm is ever-increasing for SETI, but resources are scarce. A huge disparity exists between the enormous public and scientific interest in whether we are unique in the Universe, and resources that are actually allocated to SETI research. Since 1977, the rate of refereed papers about SETI (Figure 5) is roughly flat, with the number of worldwide dedicated SETI researchers level at about a mere two dozen. With few exceptions, SETI researchers must derive salaries and academic advancement from other sources, while maintaining their SETI research on the side simply because they believe it is important and worth doing. A large fraction of SETI research is funded by private donors and foundations. Lack of a steady stream of support discourages the best and brightest young scientists from moving into this area of study. Our team and other SETI collaborations are making considerable efforts to involve undergraduate and graduate students in SETI research. However, with unreliable funding and only a handful of SETI researchers at academic institutions, the number of students trained remains small.

Our new understanding that *planets are plentiful* is rippling through the astrobiology and astronomical communities. We are bound to wonder who and what might occupy these planets. New initiatives and innovative advances in instrumentation should allow SETI to flourish through the next decade. In addition, there will likely be substantial international competition. Without sustained and supportive programs for SETI research and training, the US community risks being left on the sidelines. Even with the much needed catalyst of funds recently contributed by private foundations, leveraging both private and public sector funding is vital for creating a sustainable and growing community of SETI researchers.

Two decades ago, unknowns about astrobiology and the likelihood of extrasolar planets discouraged government funding for SETI. Today, thanks to successful NASA, NSF, and nationally supported missions and investigations, former concerns about the value of SETI research no longer apply. While there is much to learn about astrobiology and exoplanets, the relevance for advancing SETI is stronger today than ever before in the history of humankind.

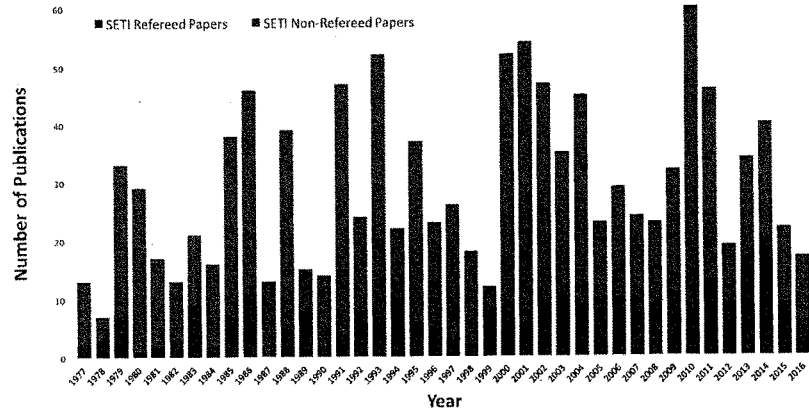


Figure 5: The number of scientific publications on SETI research for the last 39 years. (Data collected from the NASA Astrophysics Data System).

Dr. Shelley A. Wright*Short Narrative Biography*

Shelley Wright is an Assistant Professor at the University of California, San Diego in the Department of Physics and the Center for Astrophysics and Space Sciences. Wright has extensive experience working with optical and infrared instrumentation, with a particular focus on imaging cameras and spectrographs that operate behind Adaptive Optics systems on large telescopes. Her observational research focuses on galaxy and supermassive black hole formation and evolution across cosmic time. Wright currently serves as Project Scientist for the first light instrument (IRIS) for the future Thirty Meter Telescope.

Throughout her career, Wright has been an active collaborator in optical and near-infrared SETI instrument development and research. Wright has been involved with design, construction, and implementation of pulsed laser SETI instruments. Wright was a critical team member that developed one of the most advanced optical SETI experiments, and is now Principal Investigator of the first near-infrared SETI instrument and survey.

Wright received her B.S. in Physics at University of California, Santa Cruz in 2001. She served as support astronomer at the Isaac Newton Group of Telescopes on La Palma, then continued her graduate studies at University of California, Los Angeles (UCLA) in the Physics & Astronomy Department. Wright conducted her graduate research on Keck Observatory instrumentation and observations while working in the Infrared Astrophysical Laboratory at UCLA, receiving her Ph.D. in 2008. Wright then served as a postdoctoral researcher at University of California, Irvine in 2008-2009 working on instrumentation development and scientific studies for the Thirty Meter Telescope. In 2009, she received a NASA Hubble Postdoctoral Fellowship and the University of California President's Fellowship at University of California, Berkeley for her observational research program on distant galaxies. Prior to her arrival at UC San Diego, Wright was Assistant Professor at the University of Toronto in the Department of Astronomy & Astrophysics and the Dunlap Institute for Astronomy & Astrophysics from 2012-2014. Wright was recently named a 2016 Hellman Fellow at UC San Diego.

Chairman BABIN. Thank you, Dr. Wright.
I now recognize Dr. Jones for five minutes to present her testimony.

**TESTIMONY OF DR. CHRISTINE JONES,
SENIOR ASTROPHYSICIST,
SMITHSONIAN ASTROPHYSICAL OBSERVATORY,
PRESIDENT, AMERICAN ASTRONOMICAL SOCIETY**

Dr. JONES. So Chairman Babin, Chairman Smith, Ranking Member Edwards, and Members of the Subcommittee, thank you for the opportunity to testify today on behalf of the American Astronomical Society, the professional society of our discipline in the United States.

We're very fortunate in the United States to have a robust fleet of space- and ground-based observatories that allow us to make exciting new discoveries about our universe. Congress has long been a strong supporter of these programs at NASA and NSF, and for that our community is extremely grateful.

I hope to give you just a snapshot of the exciting research, technology development, and education and outreach activities that astronomers engage in. As you know from these other testimonies, not very long ago the only planets we knew about were in our solar system. Dark energy had not been discovered and supermassive black holes were not known to be common in the centers of galaxies. A lot's changed since then thanks to significant public and private support.

Today, we discovered almost 3,000 exoplanets have another 2,500 candidates. NASA's Kepler mission found an exoplanet orbiting two suns, colloquially known as Tatooine after the double star system in Star Wars. Just last week, a U.S.-led team using the European ground-based telescope announced the discovery of an exoplanet with three stars, one better than Tatooine.

Thanks to ground- and space-based observations, we now know that normal matter, the sort of stuff we deal with directly every day, makes up only a small fraction of the mass in the universe. The rest of the mass is dark matter or dark energy, which isn't even matter at all but it is driving the accelerating expansion of the universe.

Although as President of the AAS, I speak on behalf of all the astronomical scientists. I'm also an active researcher. My research focuses on the effect supermassive black holes have on their host galaxies. These black holes have occasional very large outbursts that prevent new stars from forming in their galaxy. It's amazing to think that something so relatively small in size has an impact across the galaxy many tens of thousands of light years in size.

This research has more than pure academic value. The technology that we developed to explore the universe transfers beyond our field. I want to mention just two examples. Much of the time, as you've heard, when astronomers want to study objects, they're very, very faint. They can be distant galaxies. They can be very faint objects in our own solar system. To study such faint astronomical objects, we need both large telescopes and very sensitive instruments. Although the first CCDs were made for data storage devices, astronomers recognized that they could be modified to

function as core components of highly sensitive, efficient, and stable imaging devices.

Astronomers, working with industry and the government, helped improve CCD detectors so they're part of the workhorse of instruments on ground and space-based telescopes. Variations of that technology transferred beyond astronomy and are now the crucial components of innumerable digital imaging systems, including the camera that you probably have in all of your cell phones.

And technology originally developed for observing x-ray sources in space is also used for security screening. The company American Science and Engineering where Nobel Prize-winning astronomer Riccardo Giacconi worked also developed and built the first x-ray scanners. The next time you put your bag through the Smithsonian's Air and Space Museum's scanner, take a moment to look at the AS&E label that's on the side.

But perhaps the most important technology transfer of all is the technically trained people. Astronomy is really a gateway science that brings people into STEM fields, and astronomers love sharing what we do with the public. Undergraduate Astro 101 courses enroll approximately 250,000 students each year nationwide and are taken by about ten percent of all college students, making it one of the most popular general education courses.

NASA and NSF have very active and successful education and outreach programs. This includes the Hubble program that brings formal science education to students in half of the public middle schools in the United States. Programs at NSF like the research experiences for undergraduates play an important role getting undergraduates from diverse backgrounds exposed to doing forefront research.

But even with these programs, most scientific fields including ours have a long way to go on the path toward being fully inclusive of underrepresented minorities. There are no easy answers or quick fixes, but our community is committed to doing better with the help of our colleagues at NSF and NASA.

In closing, the mission of the AAS is to enhance and share humanity's scientific understanding of the universe, where it came from, and where it's going. It's a challenging mission, and what we do resonates with the American people. Discoveries grace the front pages of major newspapers and people filled Times Square to watch Curiosity land on Mars. The public wants us to uncover more of the mysteries of the universe and to share those results with them. That is what astronomers do, and it is what funding from Congress facilitates.

It's a delight to participate in this effort as a researcher, an honor to serve as the President of the AAS, and I look forward to answering your questions here today and in the future.

Oh, and I couldn't help but notice that there are seven members of the Full Committee from Texas, including Chairman Smith and Ranking Member Johnson, who's not here right now, and it turns out that 2017 is the year of Texas for the AAS. Please accept my personal invitation for you or members of your staff to attend the society's conferences next year. In January we'll be in Grapevine and in June we'll be in Austin. Thank you very much.

[The prepared statement of Dr. Jones follows:]

Statement of
Dr. Christine Jones
President, American Astronomical Society
before the
U.S. House of Representatives
Committee on Science, Space and Technology
Subcommittee on Space and
Subcommittee on Research and Technology
July 12, 2016

Chairman Babin, Chairwoman Comstock, Ranking Member Edwards, Ranking Member Lipinski, and members of the Subcommittees, I am pleased to have the opportunity, as the President of the American Astronomical Society, to summarize the state of US astronomy as supported through the Federal agencies NASA and NSF. I provide examples of cutting edge astrophysical research, emphasize the importance of supporting basic science research, list the important research questions and outline how future missions will address them.

To begin, I would like to thank Congress for supporting the exploration of the Universe through NSF and NASA. Federal support for astrophysical research has been absolutely essential to all the recent major advances we have made in understanding the mysteries of the Universe.

Although I was not asked to discuss planetary science or solar physics today, I would be remiss if I did not mention that many members of the American Astronomical Society perform exciting planetary and heliophysics research with the support of NASA and NSF. NASA planetary science includes the New Horizons close-approach of Pluto and Charon, and the Juno mission that just successfully began orbiting Jupiter. An asteroid sample-return mission, OSIRIS-REx, is scheduled for launch in September this year. Heliophysics includes ongoing and detailed studies of the Sun, which facilitates our ability to predict potentially devastating space weather events, and the Solar Probe Plus mission that will be launched in 2018 will “skim” the surface of the Sun. NSF’s Daniel K. Inouye Solar Telescope (DKIST) will revolutionize our understanding of the Sun when it begins operations in 2019.

WHY ASTRONOMY MATTERS

Throughout history, astronomy has provided fundamental contributions to science and insights about the nature of our Universe. Over several centuries, our view of the Universe and our place in it has changed dramatically. Copernicus revolutionized our view, in the early 1500’s, when he proposed that the Sun and not the Earth was the center of the Universe. Kepler demonstrated how planets in our solar system

orbit the Sun. This work provided part of the foundation for Isaac Newton's theory of universal gravitation.

However, early in the 20th century, there was still considerable question about the size and extent of the Universe. In 1920, in the Baird Auditorium at the Smithsonian Natural History Museum, the "Great Debate" between Harlow Shapley and Heber Curtis concerned whether the Milky Way was in fact the entire Universe as argued by Shapley, or if the Milky Way was a galaxy similar to the Andromeda nebula and other nebulae, as argued by Curtis. The debate did not resolve this question. It was only through Edwin Hubble's observations of variable stars in other nebulae that it became clear that our Milky Way is only one of many galaxies in the Universe.

Even before Earth's place in the Universe was known, astronomy played critical roles in early navigation and timekeeping. In modern times, the observations of the 1919 solar eclipse were important in proving Einstein's theory of general relativity. The scientist Ralph Fowler developed the concept of electron degeneracy to explain white dwarf stars, long before this concept was established in solid state physics. Also from astronomy research, we have learned that heavy elements, including the oxygen we breathe, the calcium in our bones, and the gold in our wedding rings are all produced by stars.

THE BIG QUESTIONS FOR ASTRONOMY

Part of astronomy's appeal to the public and scientists alike is that it seeks to answer the "big" questions:

- How did the Universe come to be?
- Are there other Universes?
- Is General Relativity correct?
- What is dark matter?
- What is the nature of the dark energy that causes the acceleration of our expanding Universe?
- How do the components of the Universe change over cosmic time?
- What new exotic transient phenomena does the Universe contain?
- How are stars and planets formed?
- Is there water on other worlds outside our Solar System?
- Are there Solar Systems like our own in the nearby Milky Way Galaxy?
- What were the first stars and galaxies like?
- How did galaxies grow across cosmic time to form Milky Way like systems?
- Are we alone?

These questions excite not only professional astronomers, but the public as well, from children to seniors. To answer these questions and many more, we need large telescopes on the ground and in space that cover the electromagnetic spectrum from long wavelength radio observations to X-rays and gamma rays. As part of answering these questions, we engage students in STEM fields and spawn new technologies that impact our daily lives. As Chairman Smith has said so well in the past "Space exploration is an investment in our future – often the distant future. It encourages innovation and improves Americans' quality of life. It inspires the next generation to pursue careers in math, engineering, science, and technology." Chairman Smith's statement is still true today.

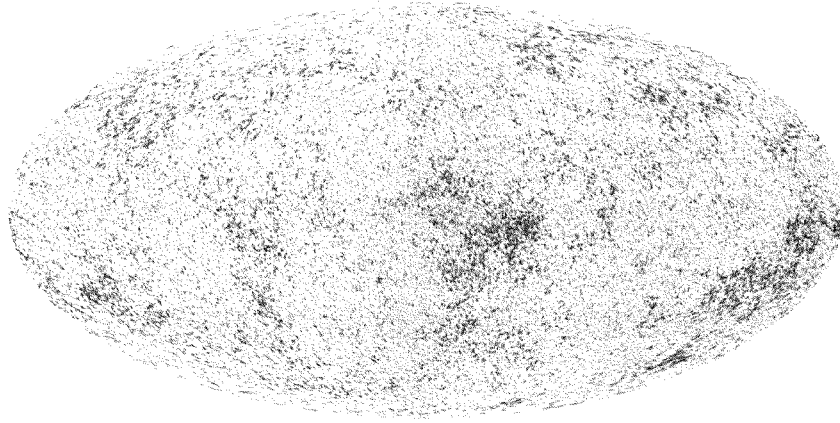


Figure 1. The small scale anisotropies of the cosmic microwave background (CMB) as observed by the Planck satellite. The CMB is a snapshot of the oldest light in our Universe, imprinted on the sky when the Universe was just 380,000 years old. The observed fluctuations reflect tiny temperature fluctuations that trace the seeds of the structures that are observed today. The observed fluctuations are used to derive the precise cosmological parameters that characterize today's "precision cosmology". (Credit: ESA and the Planck collaboration)

RECENT DISCOVERIES IN ASTRONOMY

Now is a very exciting time to be an astronomer. New discoveries are challenging what we thought we knew about our Universe. When I was a student in the 1970's, much about what we know today about the Universe was not known or was very uncertain. For example, even the age of the Universe, a very basic and fundamentally important property, was very uncertain. There were two distinct scientific camps. One group of scientists argued, based on their observations, that the Universe was about 19 billion years old, while the other argued the Universe was significantly younger, only about 9.5 billion years old.

Today our knowledge of the Universe is far better than when I was a student. Much of the basic information about the early Universe is imprinted on the Cosmic Microwave Background (CMB), the nearly uniform 3 degree radiation that permeates our Universe. This "afterglow" of the Big Bang has traveled to us from the "surface of last scattering" after electrons, protons, and helium nuclei formed hydrogen and helium atoms, allowing light to travel great distances without scattering off free electrons. Based on analysis of the sky maps of the CMB made by the US WMAP (Wilkinson Microwave Anisotropy Probe) mission and the ESA-US Planck mission (Fig 1), we now know the time since the Big Bang (the age of the Universe) is 13.80 ± 0.02 billion years, measured to an accuracy of 0.14%!

Observations from the Planck and WMAP missions also determined that matter makes up only 31% of the Universe, while 69% of the Universe is in the form of the still mysterious dark energy which drives the accelerating expansion of the Universe. And of the 31% of the Universe that is matter, most of this, 81%, is dark matter. Although dark matter emits no radiation, its presence can be inferred in individual galaxies by the motions of stars and gas and in galaxy clusters by their ability to gravitationally bind galaxies and the hot intracluster medium. This hot gas, which fills the entire volume of massive clusters, is visible through its X-ray emission and makes up most of the “normal” matter in clusters, with three to five times more mass in hot gas than in all the galaxies in the cluster (see Fig. 3). But recall that dark matter makes up the bulk of the mass in clusters.

When I was a student, no planets had been found outside our Solar System. In 1992, radio astronomers Wolszczan and Frail announced their discovery of two planets orbiting a radio pulsar. In 1995, astronomers Mayor and Queloz, from the University of Geneva announced the definitive detection of a planet orbiting a normal star 51 Pegasi. Although in 1988, three Canadian astronomers (Campbell, Walker, and Yang) published the first suggestion of planets orbiting the star Gamma Cephei, these exoplanets were not confirmed until 2003. NASA’s Kepler mission, launched in 2009, has now discovered 2373 confirmed exoplanets (out of 4943 candidate exoplanets).

The discovery of thousands of planets around stars in our Galaxy by the US Kepler mission has shown us the great variety of stellar-planetary systems, including Kepler 16b, the Tatooine system where the planet orbits its two Suns (Fig 2) and very recently, a planet orbiting three stars was reported! The great variety of planetary systems is forcing us to re-examine how planetary systems are formed. In 2017, NASA’s Transient Exoplanet Survey Satellite (TESS) will be launched with the primary goal of detecting small planets with bright host stars in the solar neighborhood, which will allow detailed follow-up observations of the planets and their atmospheres by the next generation of instruments and large space- and ground-based telescopes to search for evidence of extraterrestrial life. The Gemini Planet Imager is now directly imaging massive exoplanets to determine masses and compositions.

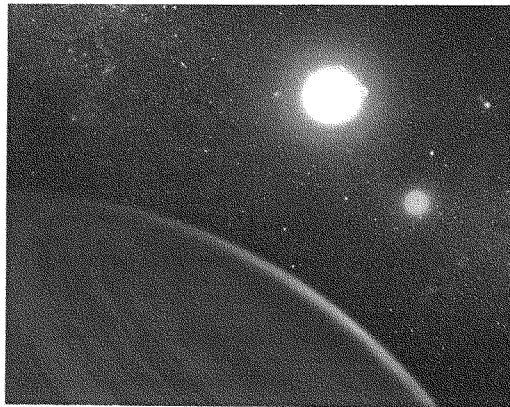


Figure 2. This artist's concept illustrates Kepler-16b aka Tatooine, the first planet known to definitively orbit two stars - what's called a circumbinary planet. The planet, which can be seen in the foreground, was discovered by NASA's Kepler mission. Credits: NASA/JPL-Caltech/T. Pyle

OBSERVING ACROSS THE ELECTROMAGNETIC SPECTRUM WITH SPACE AND GROUND-BASED OBSERVATORIES

To fully understand an object, be it a star with several planets or a massive cluster of hundreds of galaxies, each with a 100 billion stars, requires that we observe the object across the electromagnetic spectrum. For example, very energetic shocks observed in the X-ray emission of the hot intracluster medium, along with observations of radio “relics” and optical spectroscopy of cluster galaxies can inform us about how smaller clusters of galaxies collide and grow into massive clusters over cosmic time (Figure 3). Giant 8-10 meter telescopes on the ground complement space based telescopes by offering similar sensitivity in spectroscopic follow up of discoveries from space.

In the last three decades, our ability to observe the Universe at wavelengths from the microwave to the X-ray and gamma rays has improved dramatically with the launch of US supported missions including ROSAT, Hubble, Chandra, NuSTAR, Spitzer, WISE, XMM-Newton, Suzaku, Fermi, Swift, SOFIA, Kepler, WMAP, Planck, Hitomi, and the development of large ground-based optical, radio and submillimeter observatories (e.g. Gemini, Keck telescopes, VLT, MMT, the European LOFAR facility, the upgraded US JVLA, SKA, the US LIGO gravitation wave observatory, SPT, ACT, and the international ALMA). These observatories allow us to observe all types of objects from exoplanets to the birth of new stars, to the discovery of supermassive black holes and cosmic jets, to the growth over cosmic time of galaxies and clusters. ALMA is now a premier observatory for mapping the flow of cold gas onto supermassive black holes at the centers of galaxies in rich clusters. New ground based observatories, including the international Event Horizon Telescope, the Large Synoptic Survey Telescope, the Thirty Meter Telescope, the Giant Magellan Telescope and the European Extremely Large Telescope and the Square Kilometer Array are under construction.



Fig 3. The colliding galaxy cluster MACS J0717+3745, more than 5 billion light-years from Earth, is one of the most massive galaxy clusters known in the Universe. The colliding subclusters produce shocks and accelerate particles to very high energies. The massive cluster also provides a “cosmic” lens to magnify galaxies behind the cluster enabling a view of the distant universe. Background is Hubble Space Telescope image; blue is Chandra X-ray image, and red is VLA radio image. (Credit: VLA, Chandra, HST, NASA, NRAO from van Weeren et al.)

STELLAR MASS BLACK HOLES AND FIRST DETECTION OF GRAVITATIONAL WAVES

Although black holes were predicted by Einstein in 1916 as part of his general theory of relativity, the first one, Cygnus X-1, was not discovered until 1971. The two recent detections with LIGO of gravitational waves produced by the mergers of two stellar mass black holes have opened a new way of observing the Universe (see Figure 4). The US led the technology development for this incredibly challenging technological achievement. As LIGO is joined by gravitational wave observatories in Europe, Japan and India, the ability to locate sources of gravitational waves like these black hole mergers will improve dramatically, allowing the identification and study of these black holes across the electromagnetic spectrum, further enabling “multi-messenger” astronomy.

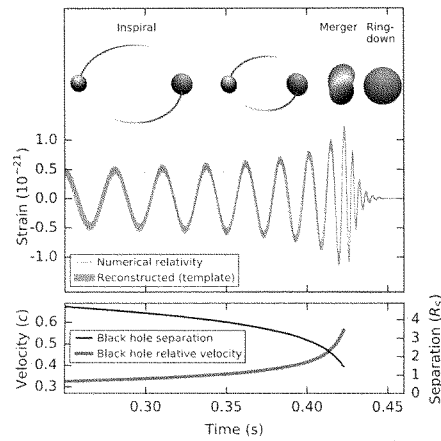


Fig. 4. Top: Estimated gravitational-wave strain amplitude from the first gravitational wave detected by LIGO - GW150914. The inset images show numerical relativity models of the black hole horizons as the black holes coalesce. Bottom: The Keplerian effective black hole separation in units of Schwarzschild radii ($R_s = 2GM/c^2$) and the effective relative velocity given by the post-Newtonian parameter $v/c = (GM\pi f/c^3)^{1/3}$ where f is the gravitational-wave frequency calculated with numerical relativity and M is the total mass, c is the speed of light, and G is the gravitational constant. (Figure from Abbott et al. 2016, PRL 116, 061102)

LOOKING BACK IN TIME

The current ground and space-based observatories have brought us closer to understanding how the Universe formed, and how it evolved over the last 13.8 billion years. When we look at very distant galaxies, we are observing them as they were when the light we see now was emitted. We are essentially being allowed to look back in time to see galaxies when they were young. Quoting from my colleague Alan Dressler, “Astronomers have an advantage over other historians: they can observe history directly – if not their own, at least someone else’s”. With Spitzer, Hubble, WISE, and large ground-based telescopes, we are able to observe very distant galaxies at a time when the Universe was less than a billion years old. Currently the most distant galaxy known has a confirmed redshift of 7.7, which corresponds to a time when the age of the Universe was only 0.7 billion years. Many of the galaxies found in the early Universe are irregular in shape and much smaller than our Milky Way. With the

launch of the James Webb Space Telescope in 2018, we will be capable of observing the first stars, likely formed when the Universe was only a few hundred million years old, only about 3% of our Universe's present age.

Determining how galaxies evolve over cosmic time has long been a major quest. Only in the past few years, have we come to understand the close relationship between galaxies and the supermassive black holes that often reside in their cores. At the center of our Milky Way lies a black hole with a mass 4.5 million times the mass of our Sun. However, in more massive galaxies, central black holes with masses as large as 1 billion to 10 billion times the mass of the Sun have been found. X-ray observations from the Chandra Observatory show very energetic outbursts produced by these supermassive black holes, as powerful as 10^{62} ergs, which likely govern the formation of stars in the centers of these galaxies.

Large ground-based optical-IR telescopes include the existing Keck telescopes and ESO's VLT, as well as the future Thirty Meter Telescope, the Giant Magellan Telescope, and ESO's EVLT, which are now in various early stages of construction. These observatories will provide very high resolution spectra of faint objects detected by future space missions. Such follow-up observations will be critical for understanding the nature of the new objects identified by future space missions.

UNDERSTANDING OBSERVATIONS BETTER THROUGH SIMULATIONS

To complement the observations, very significant increases in computing power have made it possible to carry out sophisticated simulations of many different phenomena, including how galaxies and large scale structures form, how supernovae explode, how black holes merge, how planetary systems form and evolve. In computer simulations, unlike in nature, we can change various parameters of the system and see how these changes affect the evolution of the system. Comparison of these simulations to actual observations will allow us to understand what are the key drivers.

PLANNING FOR THE FUTURE – the Decadal Surveys

In the US, every 10 years the National Academy of Sciences constitutes a Decadal Committee with the goal of prioritizing major space and ground-based astronomical missions for the next decade. The 2010 Decadal Survey "New Worlds, New Horizons in Astronomy and Astrophysics" recommended constructing new survey telescopes in space to investigate the nature of dark energy as well as the next generation of ground based optical telescopes and a new class of space based gravitational observatory to observe the merging of distant black holes and precisely test theories of gravity. WFIRST (Wide Field InfraRed Survey Telescope) will have a spatial resolution comparable to the Hubble Space Telescope, but a field of view that is 100 times larger than the HST infrared instrument. The Wide Field instrument will characterize a billion galaxies, and a microlensing survey of the inner Milky Way is expected to find about 2600 new exoplanets. To accomplish the third goal of the 2010 Decadal Survey to detect gravitational waves, NASA is partnering with ESO on the LISA project and to fulfill the fourth goal, the US will contribute to ESA's Athena mission.

Planning for the 2020 Decadal survey is now underway. As part of this process, NASA directed its three Astrophysics Program Analysis Groups to solicit community input toward identifying a small set of

major missions that should be studied and presented to the 2020 Decadal review. The outcome of this community driven process was a set of four major initiatives: The Far-Infrared Surveyor whose goals include revolutionizing our understanding of planetary system formation, detecting previously unknown extrasolar planets, unveiling the dark side of galaxy evolution, and opening up an information-rich and still largely unexplored region of discovery space. The Habitable Exoplanet Imaging Mission would directly image Earth-like exoplanets, and characterize their atmospheric content. By measuring the spectra of these planets, HabEx would search for signatures of habitability such as water, and be sensitive to gases in the atmosphere, possibility indicative of biological activity, such as oxygen or ozone. The Large Ultraviolet, Optical, and Infrared Surveyor has the driving goal to characterize a wide range of exoplanets, including those that might be habitable - or even inhabited. It would also probe the Universe from the epoch of reionization, through galaxy formation and evolution, to star and planet formation. The X-ray Surveyor would probe the high energy Universe with studies of the origin and growth of the first supermassive black holes, the physics of feedback and accretion in galaxies and galaxy clusters, galaxy evolution and the growth of cosmic structure, the physics of matter in extreme environments, and the origin and evolution of the stars that make up our Universe.

The decadal process has been strongly community driven. As AAS President, I would urge all the participating parties to continue the involvement of the community. In selecting members for the various decadal panels, I would expect that the community be represented in the broadest way and that expertise would enable impartial selection of the best science. I look forward to working with all those involved to ensure this process is successful and open.

We should keep in mind that while we justify building new observatories to address the “big questions,” often we are poor predictors of the surprises the Universe has to offer. As an example, Fred Chaffee, the first Director of the Keck telescopes, made a list of the most important discoveries made by the Keck telescopes in their first decade of operation and found that none of these were part of the original scientific justification for building Keck. As another example, when Hubble was launched and the Keck 10-meter telescopes were built, no exoplanets had been confirmed. Now, these telescopes are working together to understand the distribution and properties of other worlds. Discoveries like these change the astronomical landscape and spark new research for new generations of astronomers.

INTERNATIONAL PARTNERSHIPS

Some of our most successful astronomical facilities have only been possible because several nations worked together towards a common goal. In our quest to build the Hubble Space Telescope, we quickly realized that international collaboration would be necessary, and so NASA partnered with ESA. Similarly, for the James Webb Space Telescope, international collaboration was necessary, and the JWST partnership includes NASA, ESA, and CSA. Large, ground-based telescopes like the Thirty Meter Telescope, the Giant Magellan Telescope, the Square-Kilometer Array, and others are only possible through international collaboration. Even beyond the building of new facilities, international collaboration is vital for the scientific enterprise. Keeping the avenues of collaboration between nations open is important to the overall health of the field.

Although many NASA observatories are international projects, these missions cannot be done without US leadership. Flagship missions are a symbol of American leadership in science and space.

ASTRONOMY AS A GATEWAY SCIENCE - STEM Education and Outreach

Astronomy is a gateway science that inspires curiosity in everyone, from young children to our most senior citizens. Children are fascinated by the night sky, by what the moon looks like, even through a small telescope and by the scale of our Solar System. I love working with elementary school classrooms to build scale model Solar Systems on their playgrounds. Television programs (e.g. COSMOS: A Spacetime Odyssey) and popular astronomy lectures attract large audiences across all demographics.

Every major NASA mission has active programs to help educate, inform and excite the public about the new scientific discoveries that are being made. As one example, HST formal education programs reach *half of all public middle school children in the US*. With the sky visible on every clear night, astronomy is a unique magnet for drawing children into STEM fields.

Participation by the public in characterizing objects in very large databases has involved many thousands of people from across the globe. Astronomy related citizen science projects include Galaxy Zoo, Radio Galaxy Zoo, Sunspotter, Comet Hunters, Planet Hunters, and Disk Detective. Zooniverse has become the unofficial hub for Internet-based astronomy citizen science and has expanded beyond astronomy to include other scientific fields, and even include decoding ancient papyri (<https://www.zooniverse.org/projects?discipline=astronomy&page=1>).

TECHNOLOGY and SPINOFFS

Astronomy contributes significantly to new technology. The faintness of many of the objects astronomers want to study, from the most distant galaxies and stars in the Universe to exoplanets around nearby stars requires very sensitive detectors and active optics. So astronomers design and build some of the best detectors in the world. For example, although astronomers did not invent CCDs (they were first made by scientists and engineers designing memory storage devices), astronomers recognized the potential of CCDs for collecting light from faint astronomical objects. Astronomers worked to develop CCDs from the first noisy, flawed stage to become the excellent components now in the best astronomical imaging and spectroscopic instruments. Of course such much improved CCDs are also now in cell phones and even dentists, rather than using film, will take a picture of your teeth with a small CCD camera. JWST wavefront sensing technologies have improved laser eye surgery treatment and diagnosis of ocular diseases

While there has been some controversy over who invented the internet, it was Australian astronomer John O'Sullivan, who, as part of his work as a radio astronomer, discovered the methods now used to access wireless computer networks. Similarly submillimeter astronomy contributed to the terahertz technology used in security scanning.

My own field of research is X-ray observations of distant galaxies and clusters of galaxies. Riccardo Giacconi was one of my mentors and was the primary founder for the field of X-ray astronomy for which he received both the Nobel Prize for physics and the National Medal of Science. Giacconi's early work was done at American Science and Engineering in Cambridge, MA. This work provided the

foundation for AS&E's technology for counter-terrorism and security applications. Every visitor to the National Air and Space Museum still puts their backpacks and pocketbooks through security scanners with AS&E labels on their sides.

One of the questions often asked of scientists is what is the use of basic physics (or astrophysics) research. Certainly early in the 20th century, when Einstein developed his special and general theories of relativity, no one would have predicted that relativity would play an important role in our day to day lives. The Global Positioning Network (GPS) is based on an array of satellites orbiting the Earth, each with an atomic clock. A GPS receiver in your car or phone or airplane cockpit can receive radio signals from the GPS satellites that are overhead and accurately determine your latitude, longitude and altitude. But since the satellites are moving at 14,000 km/hr, much faster than Earthbound clocks, Einstein's theory of special relativity predicts the spacebound clocks should be ticking more slowly than the Earthbound clocks. But the spacebound clocks also experience weaker gravity than the Earthbound clocks, which causes the orbiting clocks to tick faster than their Earthbound counterparts. The net result is that time on the orbiting clocks advances slightly faster than time on the Earthbound clocks. If one wants to measure one's position on Earth to an accuracy of 20 meters, you need to be able to measure time throughout the GPS system to about 65 nanoseconds (the time it takes light to travel 20 meters). However if the relativistic offsets between the rates of the satellite and Earthbound clocks are not corrected, the derived navigational positions would have very significant errors. Quoting Clifford Will "Without the proper application of relativity, GPS would fail in its navigational functions within about two minutes."

CONCLUDING REMARKS

The past and current health of our profession is strong. The US has led in many of the recent advances in our knowledge of the Universe, from the discovery that the expansion of the Universe is accelerating, to the detection of thousands of exoplanets, and the recent detection of gravitational waves from merging black holes. We are fortunate to have a fleet of observatories, both on the ground and in space, which can operate in concert across the spectrum. Major ground based US observatories have also been built or are under construction, including ALMA, LSST, the Event Horizon Telescope and the next generation of Very Large Telescopes. These observatories will enable us to address fundamental questions beginning with "How did the Universe come to be?" to "Are we alone?"

Although three of NASA's Great Observatories are still obtaining excellent, cutting-edge observations, these observatories are aging. While plans are underway to build new flagship space observatories, as we look to the future, it would be scientifically beneficial to strive for a suite of contemporaneous missions that span the observational windows. The first of the new generation of space missions will be JWST, which will be launched in 2018. The 2020 Decadal Survey will review and prioritize the next generation of large space-based observatories.

Our community is deeply concerned about the impact of ongoing flat research budgets at NSF. While managers at NSF are striving to maintain programmatic balance—always the overarching priority of our decadal surveys—in the face of flat budgets, they have run out of options and something will have to give. History teaches us that the "something" will likely be individual research grants. So it is a very positive step that the current NSF reauthorization in the Senate includes four percent increases for NSF

through FY 2018. I hope that Congress will ultimately authorize a longer, sustained growth trajectory for NSF.

I believe that NASA and NSF are working diligently to carry out the guidance of the community as expressed in the Decadal Surveys as well as interim reviews and inputs from advisory committees. Both agencies endeavor to maximize the science results that can be obtained from the available funds. Any changes from carefully vetted plans should be evaluated with great care to ensure that the consequences do not overly impact existing projects and programs.

In addition to obtaining new observations, data archives from current and past missions provide a wealth of information enabling new discoveries. Having observations made available in public archives no more than a year after they are obtained has been critical to advancing astronomical frontiers. For example, the Hubble archive effectively doubles the number of HST papers published each year. Two of the principles of US astronomy have been openness to proposing for new observations and rapid access to archival data. Ease of access applies as well as to the astronomical literature, and the Society's journals adhere to this principle. These are models for the world. As international partnerships continue to grow in importance, these principles should be adopted for all future missions that receive Federal funding.

Thank you for listening and if you have questions, I would be happy to answer them.

NARRATIVE BIOGRAPHY Christine Jones

Dr. Christine Jones earned her A.B., M.A. and Ph.D. degrees in Astronomy at Harvard University, completing her Ph.D. in 1974. She then became a post-doctoral fellow at the Center for Astrophysics (CfA), and was subsequently a Harvard Junior Fellow before joining the Smithsonian at the CfA where she is now a Senior Astrophysicist.

Throughout her career, Dr. Jones has worked on a variety of research topics, but most recently her research has focused on X-ray studies of the hot gas in galaxies and galaxy clusters using the Chandra X-ray observatory, which was successfully launched by the Columbia shuttle in July 1999. With Chandra and other X-ray observatories, Dr. Jones and her colleagues study clusters of galaxies to measure how they grow from early times to the present. They also use Chandra to observe how energetic outbursts from supermassive black holes at the centers of galaxies produce shocks and reheat the surrounding gaseous atmospheres.

Her research has resulted in 280 refereed journal publications, which have been cited more than 21,000 times. Dr. Jones has been recognized 14 times for her dedication to her work and to her field, including the Bruno Rossi Prize for her work on X-ray emission of galaxies, several NASA Group Achievement Awards for her work on Chandra, an appointment as a Fellow of the American Association for the Advancement of Science, and an appointment as an Honorary Fellow of the Royal Astronomical Society.

Dr. Jones has served her community as a member of the Executive Council of the High Energy Astrophysics Division of the American Astronomical Society, as Deputy and later President of the IAU Division on Space and High Energy Astrophysics, and on several telescope allocation review panels, grant review panels, and advisory and planning committees. Dr. Jones has recently assumed the mantle of President of the American Astronomical Society. Dr. Jones has also sought to grow and enrich her field by mentoring high school, undergraduate, and graduate students on research projects. Indeed, her commitment is so great that for more than 20 years, she has been the principal investigator of an NSF supported Research Experiences for Undergraduates program that brings ten undergraduate students to the CfA for ten weeks each summer to conduct research.

Chairman BABIN. Thank you very much, Dr. Jones, and I hope that my scheduler will take note of that. And I'd love to be there.

Anyway, we certainly thank all of the witnesses for your testimony. And now the Chair recognizes himself for five minutes.

The JWST thermal vacuum testing will be conducted at the Johnson Space Center's Chamber A, which is the largest high vacuum cryogenic optical test chamber in the world. Chamber A was famously used for Apollo testing.

And, Dr. Hertz, if you can speak to how this unique facility supports astronomy and astrophysics missions.

Dr. HERTZ. Thank you, Mr. Chair, for that question. One of the lessons that NASA has learned over the years of launching many successful space missions is that a thorough testing on the ground is the key to making sure they work the first time we turn them on in space unlike ground-based observatories. We can't send our technicians in to fix them if that turns out to be—if we don't get them working right.

Chamber A is the only place in the country where we could do a full end-to-end test of the James Webb Space Telescope. The Webb telescope is being assembled right now at the Goddard Space Flight Center, and early next year we will be shipping it down to Houston to put it into Chamber A where we will spend a good fraction of the year doing the end-to-end test with the flight telescope and all four flight instruments inside the chamber to make sure they work as a complete system.

Chairman BABIN. Thank you very, very much. And we're looking forward to observing some of these tests.

My next question is for Dr. Olinto. One of the reasons the Hubble Space Telescope is so successful is that it can be serviced by the space shuttle. How could a deep space exploration vehicle like Orion impact future astronomy and astrophysics missions? And how would future astronomy and astrophysics missions benefit from being capable of crew servicing if they are reasonably within reach of the SLS and Orion?

Dr. OLINTO. Just repeating what Paul just said, it is really important to make sure it works perfectly before you launch—

Chairman BABIN. Right.

Dr. OLINTO. —because it's obviously a very difficult thing to do. We are very proud that the Hubble was serviced and it is so capable of doing gorgeous things, including my scarf. But going to, for example, L2 to service JWST would be a much harder job just, you know, it's much further away. So I think this is a challenge that I'm sure that if we are willing to spend a lot of money on it, we should be able to do it.

But in terms of priorities I think the best is to make sure it's really working on the ground. So servicing things far away is really challenging. On the other hand, we need to keep this capabilities developing for future missions which might become more affordable to go service something in L2, for example. So I imagine that for very far away robotics would be the way to go first so that we make sure our astronauts come back healthy.

Chairman BABIN. Okay. Thank you. Absolutely.

Now, a question to really everyone concerning the SLS. How will the capabilities of the Space Launch System impact future astron-

omy and astrophysics missions? Some of it's been addressed already. And how should the next decadal survey account for these capabilities? Who would like to address that first?

Dr. HERTZ. I'll start off, Mr. Chair. The SLS offers a number of capabilities that could be used by future space-based observatories. Primarily, it's the large mass that's capable of launching into space and the large faring that will have compared to some of the current generation of launch vehicles.

As many of the witnesses have testified, the frontiers of astrophysics require us to image things which are very far away and very faint, that means very large mirrors in order to collect enough light for us to make scientific deductions about what we're looking at. Large mirrors are both large and heavy, and the SLS can help us solve both of those questions.

As I mentioned, we have ongoing right now four studies of potential future NASA missions to will help inform the next decadal survey, and so all those studies will lay out what are the requirements for those future observatories. And if those requirements can be best met by an SLS instead of some other launch vehicle, that is certainly one of the tools that would be available for realizing a future observatory.

Chairman BABIN. Okay. Thank you. Anybody else want to take an answer to that?

Dr. OLINTO. Just echo that large mirrors are definitely a must for us, the larger the better.

Chairman BABIN. Okay. Well, that completes my line of questioning and thank you very much.

And now I would like to recognize the gentlewoman from Maryland for her questions.

Ms. EDWARDS. Thank you very much, Mr. Chairman. And thank you so much to the witnesses for your testimony. You just make me so excited just to be here. And I don't do astronomy but I'm one of those kids that went to the planetarium and laid down on the beach at night looking up at the—at stars in the sky and wondering what was out there. And so thanks for your testimony today, inspiring new generations.

I was recalling with our staff here—we were going back and forth that both the Hubble Space Telescope and Kepler both at various times in their development and operation were on the chopping blocks here in the Congress. There was a time when the Hubble was the butt of late-night jokes every night on nighttime television. And Kepler was once described as being, you know, raised from the dead or something because it was under threat. So I can't even imagine what our world and your world as professionals would be if we didn't have, you know, at least those instruments in developing and building on them for the future generations.

And so I wonder if you could comment about the role of the decadal survey in terms of informing what it is that we do and how—and the importance of staying true to it even in the face of challenges because we know that each of these programs is very, very complicated and they will face significant challenges. And it's sometimes tough for us on this side to really understand that we've

just got to weather those challenges. So I'll just—that's like a freebie, anybody wants to take it.

Dr. OLINTO. I can go first because I am very proud of that process, so much so that my project in the last decadal survey was ranked number four on one panel and didn't make it to the end. So I got to be chopped, and I still think this is the right process. So, you know, I think we need to always prioritize based on the available resources and also the available technology to be able to be always successful. So we don't want to waste anybody's money, no taxpayer's money.

And this is a huge effort within the community. We spent a lot of time trying to tell our colleagues, and I think the format that we set up, which is really, you know, merit-based and having our reviews by colleagues of what we are proposing, a really good way to sort out the priorities—the top priorities for large programs. And some of us that don't get to get their project in have to be conscientious that that was the right process. And I think we have had great success exactly for that because if we weren't following that, we would be in a much harder situation. So I think it's a brilliant process.

Dr. HERTZ. I'm pleased to—well, first of all, Representative Edwards, I want to say that I bet every single one of us were kids who laid on the beach and looked up and observed the night sky and were excited by it.

I'm pleased to say that at NASA in astrophysics all of our missions—our mission decisions are driven by the recommendations and priorities of the decadal survey. Our large missions are those missions which are prioritized to be done first in the most recent decadal survey, and our smaller missions are selected through open competitions, which was also a recommendation of the decadal survey.

And so, you know, by following the decadal survey, we are assured that we are realizing the highest priorities of the science community and addressing the broadest possible range of science.

Ms. EDWARDS. Thank you. And can you add to that, you know what is the—and, Dr. Ulvestad, if you would comment, what's the challenge of, you know, trying to figure out not just what the priorities are but trying to project what some of the challenges might be so that we get closer on the money front because I think that's where we get held up.

And then—and add to that, what is—what are the threats to U.S. leadership if we don't engage in a process right now?

Dr. ULVESTAD. So first, I'll say that we, too, subscribe very rigorously to the decadal survey in setting priorities for ourselves. And one of the challenges we face is we—as you alluded to is that the decadal survey committee has to make assumptions about what future budgets are going to be, going out 5, 10, 15 years. And so they gave us a—they give us a program, a set of priorities based on some projection.

And as you may know, the decadal survey came out in 2010 right about the time that there were difficulties in the banking community and so on. And so we haven't realized the budgets that were recommended or that were sort of believed by the decadal survey. So a really important part of the decadal survey is that they not

give us a laundry list but that they give us priorities, and that way we're able to adjust to circumstances that are not exactly what they assumed.

So decadal surveys should always be aspirational. They should always reach for the stars that we all laid and looked at. And we won't be able to do everything they recommend, but by them recommending a compelling program and by them doing a good job of prioritization, that really is one of the best ways that we can react to budget circumstances that are inevitably different from what they assumed.

Ms. EDWARDS. My time's up. Thanks, Mr. Chairman.

Chairman BABIN. Thank you. I'd like to now recognize the Chairman of the Full Committee, the gentleman from Texas, Chairman Smith.

Chairman SMITH. Thank you, Mr. Chairman. Let me direct my first question to Dr. Hertz and Dr. Wright. And it seems to me that one of the most promising fields of discovery right now may be detecting optical transmissions from other worlds. And I was going to ask each of you if you could give us an update on what's going on in that field and what our hopes are. And, Dr. Hertz, if you'd like to go first.

Dr. HERTZ. Well, I'm going to defer to Dr. Wright.

Chairman SMITH. Okay.

Dr. HERTZ. This is not an area that NASA is currently pursuing, and I don't consider myself an expert at all in this area.

Chairman SMITH. Okay. Well, one, I regret NASA's not pursuing, but, Dr. Wright?

Dr. WRIGHT. I spoke a little bit about the programs on the optical SETI and the infrared study front. Radios had, you know, 50 years to get a stronghold in the SETI community—

Chairman SMITH. Right.

Dr. WRIGHT. —while I would say the optical SETI community or laser SETI in particular is still in its infancy. We're still trying to make use of the technology that's on hand. There are many things that we can do and there are many scientists that are interested in doing data mining on all the astronomical data sets that are already there from the very large array to the Arecibo to Hubble Space Telescope, even Kepler, and that involves getting software engineers involved, other astronomers to think creatively about how they can actually go in there and data mine unusual signals. And so one promising area where people want to move to is look at existing data sets and try to see if we can get optical transmissions.

Our team and others are designing a new all-sky/all-time optical SETI and infrared Wide Field Infrared SETI experiment which we're seeking funds to, and we have a meeting coming up in August to go talk about the next phases for this.

Chairman SMITH. Okay. Thank you, Dr. Wright. And, Dr. Ulvestad?

Dr. ULVESTAD. So I just wanted to mention we talked about the Large Synoptic Survey Telescope earlier.

Chairman SMITH. Yes.

Dr. ULVESTAD. That telescope will see of the order of 10 million transient sources per night. That is a source that isn't there in a

catalog but is brighter or fainter or wasn't there at all. And I think given the power requirements of lasers, people aren't going to be pointing their lasers to us all the time, so when that telescope comes up, I think its ability to survey large parts of the sky rapidly and compare them to the existing data sets will be very powerful, but it will require the kind of data mining that Dr. Wright just referred to understand what might in fact be a laser-related signal.

Chairman SMITH. Okay. My next question was for you, Dr. Ulvestad, and that is what discoveries do we expect in, say, the next five to ten years when it comes to exoplanets?

Dr. ULVESTAD. So there's a couple things that I expect we will see over the next few years. I mean, discoveries by their very nature are not easily predictable, but we build capabilities and we can sort of understand what kinds of discoveries those capabilities can be sensitive to. So one is with our partners at NASA we're working on this very high-resolution spectrograph that will go on a telescope in Arizona and be able to measure masses of planets similar to Earth, so I expect we will get specific mass measurements of some more Earth-like planets from that over the next five to 10 years.

A second is with our Gemini Observatory we have an instrument called the Gemini Planet Imager, which enables us to image planets like Jupiter in Jupiter-like orbits around stars and actually to get low-resolution spectroscopy at the same time. So I think we'll be learning more about the atmospheres of some of the extrasolar planets. And those observations will drive theoretical understanding of formation and evolution of planetary systems.

Chairman SMITH. Okay. Thank you.

And, Dr. Olinto, is there sufficient coordination between NASA and the National Science Foundation when it comes to astrobiology?

Dr. OLINTO. I think the answer is yes. And I was at the AAAC as a member in 2003 to 2006, and at that time I don't think the two gentlemen next to me, the equivalents, would have each other's cell phones and before the testimony today were joking that they could exchange and give each other's testimonies. So I think the coordination has been really wonderful.

One of the things we are looking into in terms of the coordination is near-Earth objects because LSST has the capability, per the decadal survey recommendations, to search for near-Earth objects, which is a mandate for NASA to implement.

Chairman SMITH. Okay.

Dr. OLINTO. So these things will need to be coordinated, too, so we're looking forward to that upcoming coordination between the two.

Chairman SMITH. Good enough. Thank you.

And, Dr. Jones, thank you for the invitation to the conference. Since I represent part of Austin, I will be there next June.

Dr. JONES. Thank you. We will welcome you.

Chairman SMITH. Thank you. I yield back, Mr. Chairman.

Chairman BABIN. Thank you, Mr. Chairman.

I now recognize the gentlewoman from Oregon, Ms. Bonamici.

Ms. BONAMICI. Thank you very much, Mr. Chairman, and thank you to all the witnesses. We really appreciate your expertise.

I want to ask you a little bit about international cooperation, which is something that we discuss a lot in this Committee. Dr. Hertz, I understand that NASA was not able to lead the large-scale x-ray and gravitational wave missions recommended by the decadal survey. What is the status of the NASA partnership with the European Space Agency on the ATHENA and L3 missions which will address those areas? And I wonder if you could talk a little bit about how important it is for the United States to be involved in those missions.

And also I want to bring in Dr. Wright because you mentioned something about the FAST telescope in the SETI work. And can you talk about the potential for collaboration? While we still need to of course maintain our U.S. leadership, are there some areas where we're competing rather than collaborating? Dr. Hertz?

Dr. HERTZ. Thank you. That's a great question. I'd love to speak on that topic. Pretty—probably 80 percent of all of NASA's astrophysics missions are international partnerships, which is most—virtually all of them, and all of our future large missions are envisioned to be partnerships with our international partners.

In order to make the kind of breakthrough discoveries that we look forward to in the future requires large and therefore expensive observatories in space, and we're beyond the place where the different space agencies want to put up competing and similar observatories. So we are constantly coordinating with each other on what our future plans are and looking opportunities to partner.

The James Webb Space Telescope is a partnership between the United States, the European Space Agency and the Canadian Space Agency. We are in discussions with a number of space agencies about partnerships on the WFIRST Observatory for the 2020s. And we have talked to the European Space Agency about partnering on their next two large astrophysics observatories, the ones that you mentioned, the ATHENA x-ray observatory, and we have a very mature understanding of what NASA is likely to contribute to that observatory as it goes through the European process of being approved.

And then in—further out in the future the Europeans have made a decision to lead a space-based gravitational wave observatory, which is a high priority of both of our communities. We have expressed a strong interest in partnering in that. We are under—we are engaged in discussions about what our role might be and for—and we have been for the last number of years investing in technology development here in the United States to make sure that we have developed unique technologies that we can bring to such a partnership and make a U.S. involvement in such an observatory a win-win for both partners.

Ms. BONAMICI. Terrific. Thank you.

Dr. Wright, on the SETI work is there room for progress on that?

Dr. WRIGHT. Yes, I'll just—I'll comment on the FAST telescope in China. There is a collaboration going on with Berkeley right now to help with the receiver. So as I said, the dish is already made but they have to work on the electronics and the antenna to actually detect it.

There is—the frequencies for which they cover it are slightly different than Arecibo, so there's some—there's competition on par-

ticular frequencies but on others there are not. And it's not clear to me yet or I don't think I could comment on whether the Chinese scientists want to collaborate with the SETI work and how we would work together within it.

I'll also add just one statement that the group—a group in Italy has been trying to push on optical SETI and trying to collaborate with us and get our understanding of the technology there as well.

Ms. BONAMICI. Terrific. And, Dr. Jones, I want to ask you, in your prepared statement you note the importance of making observations publicly available no more than a year after they're obtained, so can you elaborate a bit on why that's so important to advancing the science, and perhaps following up on Ms. Edwards' questions about how we talk with our constituents and the public about why it's important to invest in astronomy and astrophysics and science especially with, you know, long-term planning that's so needed might—making observations publicly available help in communicating the value of your work with the public?

Dr. JONES. Sure. I mean, the archives are tremendously important not just to astronomers but to anybody who wants to look at the observations. There are large archives of the Hubble, of the Chandra, of all of the major missions, as well as the ground-based missions. NOAO has archives of the 40 telescopes I think we're—which are archived since 2004 and NRAO also has large archives of the radio observations.

Ms. BONAMICI. Just in the remaining time, are there some examples of where observations conducted with federal funding are not made publicly accessible and available?

Dr. JONES. No, I think they're all made accessible on a timescale no longer than a year. Some are made sooner, but it's a tremendous research. So much of what, you know, people have discovered they've discovered from the archives not because they were looking to propose to do something but they find it in the archives. And that's—

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

Chairman BABIN. Thank you. I now recognize the gentleman from Oklahoma, Mr. Lucas.

Mr. LUCAS. Thank you, Mr. Chairman. And, Dr. Wright, when the general public focuses on SETI we live in a time where it wants immediate gratification, things happening right now, but in some ways isn't this kind of like a junior high dance? We've been making noise on this planet now for—since Mr. Marconi—a century probably? So the noise wave is, what, 80, 90, 100 light-years out? If you're past that point, then there's no indication that we're here to the rest of the universe. Fair statement? Therefore, part of the challenge of finding something—

Dr. WRIGHT. Well, so—

Mr. LUCAS. —is someone looking for us, too?

Dr. WRIGHT. One of the interests for NASA mission and NSF missions are for extrasolar planet atmospheres. So there are other means to detect whether there are biosignatures in the atmosphere to know whether there's life there. So they may know we're here, whether they're beyond listening to I love Lucy 90 light-years out.

But we're just still in our technological infancy, right? This is—

Mr. LUCAS. Exactly the point I was trying to make.

Dr. WRIGHT. So the standpoint for SETI is that hopefully we maintain our technology and civilizations much longer, and they would be advanced thousands or hundreds or hundreds of thousands of years longer than us so they would have other means for this.

Mr. LUCAS. Along that line, that means that we have to maintain our basic investments in not just technology but people. But, Dr. Wright, to you and Dr. Olinto, discuss for a moment the nature of the astrophysics research programs in American universities. How many are there? How do we compare to 10 or 20 years ago? What kind of facilities do they have to work with, that next-generation who will come after all of us in this room? Where are we in this country right now?

Dr. WRIGHT. I think we're doing quite well. I think that there's been no greater interest now than for astronomy and astrophysics. The facilities we have, we have many ground-based observatories that we use through universities, small-based facilities that have been excellent for trying to test innovative new instrumentation on, which is very important before we bring them to larger ground-based telescopes or we give them to NASA to put on space-based telescopes.

There's heavy student involvement. In fact, the enrollment is even higher for astrophysics bachelor's degrees. Those programs have spread through academia. And there's a greater interest within Ph.D., which I think has already been commented by the panel. A Ph.D. in astrophysics is a great springboard to any of the STEM fields.

Mr. LUCAS. Dr. Olinto?

Dr. OLINTO. Thank you for that question. I agree it's really wonderful times, and the number of students and interest is just growing. But as I mentioned in my statement, one of the challenges of flat budgets is that the facilities which we really love to build and want to use do keep growing because, you know, they have to be constructed, operated, there's inflation. So it's much harder to protect the grants program and the midscale program, which is where the new ideas and the new people get formed.

So this is the big challenge right now in trying to make sure that the future will be as wonderful as the present is to really find a way find a way to protect this most flexible part of budgets, which is the individual grants program.

And I was just visiting her institution, and on the board there is the plot that we wrote in the AAAC with the proposal pressure going high, the pressure is so much higher that much fewer grants are being able to be funded.

So I think this is the challenge we are facing now that we should keep an eye on that because it obviously doesn't come in as a flag-ship mission. It's always sort of the small programs, but those are really where the new blood comes in. So—

Mr. LUCAS. But you're confident the blood exists—

Dr. OLINTO. Oh, definitely.

Mr. LUCAS. —if the resource is available—

Dr. OLINTO. Yes.

Mr. LUCAS. —there for them to do their work?

Dr. OLINTO. Exactly.

Mr. LUCAS. It does exist?

Dr. OLINTO. Yes.

Mr. LUCAS. Dr. Hertz, you mentioned the nine Earth-like planets so far. What's the range in light-years away closest to farthest, just rough numbers?

Dr. HERTZ. Yes, I certainly don't know that off the top of my head. I'd be glad to take that question for the record and get back to you.

Mr. LUCAS. That's a fair response. Thank you.

I yield back, Mr. Chairman.

Chairman BABIN. Thank you very much.

Now, I'd like to recognize the gentleman from New York, Mr. Tonko.

Mr. TONKO. Thank you, Mr. Chair, and welcome to our panelists. Can—and this is a question for any of you. Can you characterize the current representation of women and minorities within the astronomy and astrophysics communities?

Dr. JONES. I can start with that. The numbers are growing but the numbers are still very small. Having three of us here does not represent that there are a large number of women in astronomy, but the numbers are growing. The number of underrepresented minorities is not as large.

We've had an REU program at Smithsonian for the last 20-something years. I've been PI of that. We take 10 students each year. This last year we had 300 applications. We've always had at least half of them are women, and we have a few—not as many as we'd like—of underrepresented minorities, but I think those NSF programs are tremendously important for bringing in women and underrepresented minorities.

Mr. TONKO. Yes. To any of you—and yes, Dr. Ulvestad—is there something that can be done in a targeted way that will improve those numbers?

Dr. ULVESTAD. Yes. So in—I'm not an NSF lifer. In my pre-NSF life I chaired the decadal surveys demographic study group, and Dr. Jones was actually a member of it. So I think on the gender side we see substantial increases in the number of women in the physical sciences and astronomy. I think that the numbers, if you look at the undergraduate level in astronomy, are approaching 40 to 50 percent. And one of our challenges is the—as you get to the higher levels in academia, those numbers tend to get smaller. And so a challenge us to us as a society is really how to maintain the interest of the people who are coming in as undergraduates.

On the underrepresented minority front, I think the physical sciences in general have not done very well. We have specific programs in our division, in our materials research division in NSF, but I'll point out that NSF-wide NSF has just started a new initiative called INCLUDES—and it's a long acronym; I don't remember exactly what it stands for—that's specifically aimed at underrepresented minorities.

We recently had our first round of pre-proposals for that and got over 600 pre-proposals that will be winnowed down to full proposals that will be invited. So I think NSF as an institution is trying very hard to sort of get these programs going.

I think that one of the issues for NSF is that we can address things at sort of the college and postgraduate level, and a lot of the issues relating to representation start much earlier in careers.

Mr. TONKO. Thank you. And the—to Dr. Jones and perhaps Dr. Olinto, what's the impact of low proposal success rates on the nature of the projects that get funded? In this high-pressure environment is there a sufficient support for the more long-term investigations that don't have a clearly defined result within a couple of years?

Dr. JONES. I—the low proposal rate makes it very hard for people. They're just—you know, when only one proposal in 10 roughly is being accepted I think it's discouraging. The funds that usually come in because those proposals are successful are usually the ones that support graduate students and postdocs so it makes that—you know, you can't support as many of the younger people who are coming up. So, you know, it is very—you know, it's hard and it's discouraging for members of the community.

You know, in theory the best science, the very top ten percent is getting done, but much of the science is really excellent and should be supported. So—

Mr. TONKO. And Dr. Olinto?

Dr. OLINTO. To add to this, it's difficult in many respects and especially because it used to be 30 percent and now it's 20 so the change makes, you know, people propose more because they used to get grants. So folks that had support stop having support and new folks coming in will then have to fight even harder.

And what happens is you have excellent reviews that don't mean funding. So when you write an excellent proposal and you get no funding, then you don't know what to do the next year because, you know, how can—they can't go better than excellent. So if we leave excellent proposes on the chopping block, that is a problem.

If we—you know, we don't have a perfect number, but the—historically, the 30 percent seemed to have been a very healthy way to keep excellent and very good science and, you know—because when you're squeezing the excellent out, you're also squeezing the risk, right, because we know that those three will probably be okay. This one which takes a little more risk will not. You know, we probably don't fund that because we don't know. And that's not how science should be done, right? We should really gain from a little bit of high-risk investment, obviously not all of it of the portfolio. So it's very difficult right now because of the decrease. So anyway—yes.

Mr. TONKO. Well, my time is expired. Let me thank you all for participating today.

And with that, Mr. Chair, I yield back.

Chairman BABIN. Thank you. I now recognize the gentleman from California, Mr. Rohrabacher.

Mr. ROHRABACHER. Thank you very much, Mr. Chairman, and thank you to our panelists today. It's been very thought-provoking.

I've always supported astronomy. I've been here 28 years, and I buy on and I bought on to the idea that astronomy helps us with a basic understanding of the universe not just out there but down here as well and expands our fundamental knowledge base, which are two very laudatory goals.

But number one, doing this is an expensive proposition and it's an expensive proposition that benefits all of mankind, not just Americans. And so I was heartened to hear the efforts that are being made on international cooperation, and I think that that should be expanded.

I didn't hear any cooperation with Russia. Is our current relations with Russia, which are very dicey right now—is that preventing us from having the type of cooperation in this area that could be beneficial to both our countries?

Dr. HERTZ. Thank you for the question. No, I don't think so. I mean, Russia is a very strong partner on the International Space Station with NASA, and we're very pleased to have their partnership on that project.

Mr. ROHRABACHER. Okay. Well, that's the answer. Thank you. I'm glad to hear that. I think sometimes we need to—when we have adversaries, we need to find ways of cooperating that can actually lessen the tension between people who have different points of view and countries that have different points of view.

One of the underappreciated services provided by astronomy and by this area of science that we're talking about is an early warning system that could alert us to objects coming from space that could cause enormous damage if not the ultimate damage to the Earth. And that is something that is an immediate payback. Rather than just expanding knowledge, we're actually getting a warning that could be utilized—which we have not yet put the system in place—to deflect an object that might be coming from space.

One of the prerequisites in order to set something like this up, which has been a long project of mine, one of the assets that we would have is the Arecibo telescope. And Dr. Ulvestad, there's been some statements that you've made that indicate that Arecibo, we were in the initial steps of mothballing it. Do we have other assets that can spot an object that far out and actually chart its course so that if ten years out there's an object there that would be hitting the Earth—I understand Arecibo provides that service. Do we have other ways of providing that service intact now?

Dr. ULVESTAD. So, first, I'll say we haven't made any decisions about what the future of Arecibo is. We're studying a variety of options. But in terms of detecting objects far out, what you really need for that is a survey telescope with a very wide field of view, which Arecibo is not. So Arecibo's radar can be used to characterize the properties of an object, say an asteroid that is already known about that you can point out.

In terms of the NSF investment, the LSST, which can survey the sky and as we said would detect——

Mr. ROHRABACHER. Is that already in place?

Dr. ULVESTAD. No, that's being built. That will be——

Mr. ROHRABACHER. That's not in place so we don't have something in place that would—if we mothball Arecibo this year that would be immediately taking over that particular threat and handling that?

Dr. ULVESTAD. Well, Arecibo, as I said, is not a survey telescope so it can only do radar characterization of asteroids that——

Mr. ROHRABACHER. But also——

Dr. ULVESTAD. —are already known about. So——

Mr. ROHRABACHER. Radar calculations, by the way, of where it would actually threaten the Earth?

Dr. ULVESTAD. No, what they actually do is they do radar assessments of what the composition of the object is because if it's like a rubble pile versus a solid iron mass, that will have a very different impact.

Mr. ROHRABACHER. The Arecibo telescope is not involved with charting the actual potential of an object to hit the Earth?

Dr. ULVESTAD. It's involved with tracking.

Mr. ROHRABACHER. Yes.

Dr. ULVESTAD. It can also be done with optical and infrared telescopes.

Mr. ROHRABACHER. It could be done?

Dr. ULVESTAD. Yes and is done.

Mr. ROHRABACHER. Is being done?

Dr. ULVESTAD. Yes.

Mr. ROHRABACHER. So your testimony today is that Arecibo is not providing at this time a service that is not being provided by someone else?

Dr. ULVESTAD. So as I mentioned, the radar characterization is unique to Arecibo, the characterization of the properties of an asteroid.

Mr. ROHRABACHER. Right.

Dr. ULVESTAD. Now, NASA also has a radar at Goldstone, but that's a smaller dish so the distance is not as far.

Mr. ROHRABACHER. Right. So being able to determine, as you say, what the composition is is not something that tells us whether or not that is a threat to the Earth?

Dr. ULVESTAD. It tells us something about whether it's a threat to the Earth. I think that it doesn't tell us uniquely about its path.

Mr. ROHRABACHER. Okay. Well, Dr. Hertz, could you give us your answers to that?

Dr. HERTZ. I certainly agree with everything Dr. Ulvestad said. He mentioned the Goldstone radar that's part of our deep space network. It's also used for radar characterization of asteroids. And unlike Arecibo, it can be pointed. Of course Arecibo cannot be moved sitting in a valley the way it does.

Mr. ROHRABACHER. And, Dr. Olinto, do you agree with—

Dr. OLINTO. Yes. I think there are many survey telescopes that are working now, Pan-STARRS, Dark Energy Survey, other survey telescopes of the type that LSST will be another huge next-generation improvement on what we already have. So there is a menu of things that one can do, but LSST will certainly add a huge amount to this issue.

Mr. ROHRABACHER. Yes. Now, again, I'm really looking at—and, Mr. Chairman, what's important is not what we are planning to do but what we have. And quite often, for example, when I was Chairman there in your seat, we passed a bill called the Pete Conrad Astronomy Awards Act, which gave people awards for discovering the biggest Earth object out that might threaten the Earth.

And, you know, it's just a very small amount of money, but, we've never appropriated the money for it. So it's one thing to have a plan and say, well, Arecibo won't be needed because we've got this other group telescope and it's on the way. Until it's there and

until it's appropriated and actually put in space, we have to calculate on what capabilities we have at this point.

And while I agree with you that the decadal study should show what's important, what's really important is making sure our Earth isn't destroyed by some space object and all of us die. And if there's any other priority, I think that would have to be the top priority. And we need to make sure that we don't have holes in the system as we are putting—we're planning to put something up. Let's make sure we keep Arecibo and other assets until those alternatives—

Chairman BABIN. Okay.

Mr. ROHRABACHER. —are in place.

Chairman BABIN. Thank you.

Mr. ROHRABACHER. Thank you, Mr. Chairman.

Chairman BABIN. Thank you. The gentleman's time is expired.

Okay. Mr. Beyer from Virginia.

Mr. BEYER. Thank you, Mr. Chairman. And, you know, we've had—America's had a sad week, a rough week, so thank you so much for coming here with so much optimism and so much energy, so much belief that we're doing a lot of things really well.

And by the way, I have two of my interns here today, Alexa and Max, but I bring up Max because his favorite movie is *Interstellar* so he's thrilled to be here.

So, Dr. Wright, Fred Drake 1961 came up with the famous Drake Equation that was going to predict how much intelligent life there'd likely be in the universe. That was before we had all these very cool telescopes. Based on all the research we've been able to do, you know, looking much deeper into space, how has that equation changed? What does it predict now?

Dr. WRIGHT. So I think the key one especially back at that time was understanding the number of extrasolar planets. At that time it could have been one in a million or it could be 100 percent. We actually had no idea. And with this increase, we basically have 22 percent, right, it's one in five, that says every sun-like star has another Earth-like planet. I always tell the students count in fives. Go up and count five stars; there's another Earth-like planet staring back at you. That's huge.

But as Carl Sagan pointed out and the Drake equation it's L. It's the lifetime of a civilization that really makes the big factor on the number of communicating civilizations. And so really it's how long a civilization we last. The lifetime of the universe is very long, billions and billions of years. Life here on our planet has been here for 3 billion years, but our civilization has only been here for 10,000, so it's a sliver of time.

I just—SETI takes time, patience, and diligence and understanding, and projecting where our technology will go.

Mr. BEYER. Great. Great. Thank you very much.

Dr. Jones, I've always been fascinated by the oscillating universe model. It's going to expand until it gets—and then it will contract. But now that we know that the universe is accelerating, what does that suggest for the oscillating universe model?

Dr. JONES. I think we will probably—this will be a one-way trip. We will be expanding and we will not be collapsing again so, sorry.

Mr. BEYER. We—

Dr. JONES. It's not—it's sort of not the optimistic view but——

Mr. BEYER. So we're back to linear time then?

Dr. JONES. Yes, I'm afraid so.

Mr. BEYER. Darn.

Dr. JONES. Yes.

Mr. BEYER. Dr. Hertz, were you like born to be a physicist with that name or——

Dr. HERTZ. Either that or a car rental agency.

Mr. BEYER. So, Dr. Hertz, one thing I haven't heard today is whether we're making any progress on understanding why matter in the universe is so asymmetrical. Why is there so much more matter than antimatter?

Dr. HERTZ. Yes, I'm going to pass that to Dr. Olinto——

Dr. OLINTO. All right.

Dr. HERTZ. —because that's one of her areas of research.

Dr. OLINTO. I'm itching to reply. So that's a very hard question why there's matter and not antimatter in this room, and we're very lucky that that's the case. Otherwise, we wouldn't be here because matter and antimatter annihilate. And this has to do with fundamental physics, which a previous member also mentioned. And I think that is why these broad—you know, this large piano that we use can address issues that relate to the early beginning.

So one of the big questions is how did gravity separate from the other three forces and how that process which we—you know, is beautiful to talk about, you know, with family, at parties but it's also something we can measure. And so that's to me the most exciting part. So many answers to the questions, the fundamental questions you're having have to do with, you know, what is dark energy, including the future. If dark energy the case, we might heat up again so we can choose fire again maybe between fire and ice.

But the early moments of the universe we can address by looking at the microwave background. And this is one of the many areas of research that, you know, the portfolio of the decadal survey is considering and also investing on. And it is an interagency—both NASA, DOE, and NSF, the three agencies we oversee, are investing very heavily on looking at these primordial microwave background patterns. By looking at the polarization of this light which comes from the Big Bang we can tell some properties of gravity at the time. And then that will connect to the fundamental physics that separated matter and antimatter, for example, so it's all a very interesting pursuit also.

Mr. BEYER. Is all this tied together, Dr. Olinto, while you have the microphone, because you're looking at dark matter also and dark energy.

Dr. OLINTO. Right.

Mr. BEYER. All related?

Dr. OLINTO. We don't know. So we don't know. We have a very good way to try to detect dark matter directly, and this is a huge effort. DOE and NSF are involved. Dark energy we are measuring as well as we can. It's much harder to detect. It would be easier if we could get out of our universe. Then we could measure it from the outside, but the inside is really, really challenging.

It is—there are theories that connect the two and that would make sense since there are two unknowns. Maybe they have some-

thing to do with one another. But it may be that nature, just like in exoplanets, are much creative and we don't really know the answer.

Mr. BEYER. Okay. Thank you all very much. Mr. Chair, I yield back.

Chairman BABIN. Thank you, Mr. Beyer.

Now, I recognize from the gentleman from Illinois, Mr. Hultgren.

Mr. HULTGREN. Thank you, Chairman. Thank you all so much for being here. Thank you for your work. And this really is an exciting and important hearing for us all to learn about and hear about the state of astronomy, astrophysics, astrobiology research in the United States and also internationally. These are certainly some of the toughest fields requiring the best and brightest to devote lifetimes to their field with no guaranteed or big economic payoff. It takes a passion and it's inspiring for me to watch your work, and I want to thank you for your work.

In the Committee, we will certainly continue to follow the recommendations of the decadal survey. And there are countless big ideas or future projects we could be discussing, but we all know that none of this can be ever even impossible if we're not inspiring the next generation to follow in your footsteps. Often that takes just a small spark in a young person's mind, maybe a burning question, a first telescope, robotics competition, simple reassurance from a parent, a friend, or a mentor that this is something you can do. And we need you to do it.

So I want to just ask, and I've asked this before in other committee hearings, but I'll start with Dr. Jones and maybe if we can just go down the line. It's helpful for me because you certainly are some of the best and brightest in your field, but I've noticed for experts in the STEM field that there is no single pathway to get to where you are. So just some simple questions. I wonder if you have any thoughts.

When did you know that this was something you wanted to do? Who inspired you? Feel free to give a quick shout-out to a teacher or mentor. They always could use the credit and recognition. So if you could maybe just let us know kind of your path if there was someone that inspired you and what it was, that maybe first spark, that idea that, hey, this is something interesting and something I could do.

Dr. JONES. I've been lucky to have a number of mentors. I think beginning—I grew up in—near Dayton, Ohio, everybody likes Dayton. Good. Good. There was an honors seminar in metropolitan Dayton, and I went to that. We had weekly lecture. Kids from different high schools came in.

And for me some of the most exciting were on the neutron stars, these spinning pulsars and the lectures were given by scientists at Wright-Patterson Air Force Base. And I worked when—then when I was in college I worked for a summer or two with somebody at Wright-Pat for those summers and it was terrific. So that's how I started.

Mr. HULTGREN. Dr. Wright?

Dr. WRIGHT. I think I knew as a little girl that I was addicted to the stars and the universe and trying to understand it. Probably the most formidable experience was in middle school. My science

class, they decided to play the Cosmos series by Carl Sagan, and I was hooked by watching those. And then I, too, have had many mentors thankfully. When I went and did my physics degree at the university, I had exposures to telescopes, scientists, instrumentation, working in labs, and I think having that hands-on experience was vital for me.

Dr. OLINTO. I started more interested in physics than in the universe because understanding how things move, how things drop and the basic laws of physics to me was so much easier than human beings. But very soon after getting interested in that I realized how the universe is the best place to actually learn more about physics because it has all kinds of systems. It takes everything to the extremes. So it's been a wonderful path.

And I have many other interests high school but certainly high school teachers were really important, also my parents. My father always challenged me for all kinds of math quizzes. So the Cosmos series, which aired in Portuguese in Brazil. So the outreach is really broad in that sense. So I think for all this production that happened here. And also the Apollo missions made a big impression for me as a kid.

Dr. ULVESTAD. So I was really good at math, and when I was in high school in my physics class, not knowing what I wanted to do, I remember a visiting professor from the University of Southern California, and it pains me to say that as the UCLA graduate, but that professor came and talked to us about cosmology, and that got me really interested in astronomy.

And then I took advantage—in Los Angeles they have something called the Griffith Observatory, which is in the largest public park in L.A., and you can't imagine that you can see much of a dark sky from Los Angeles, but they had educational programs and a planetarium, and that really got me excited so that when I went to college I majored in astronomy.

Mr. HULTGREN. That's great. Thanks. Dr. Hertz?

Dr. HERTZ. Well, I was a child of the '60s and I grew up just loving to read about all the NASA missions that were going on. We lived in Atlanta and my father gave into my love by driving us down to the cape before the Apollo launches and we would camp out on the beach and wake up the next morning and watch them blast off to the moon. And so that set my path.

Mr. HULTGREN. That's awesome. Well, again, thank you all for your work. We appreciate it. Thanks for inspiring others as well. It's so important and that's our only hope truly is for our young best and brightest to be willing to follow in your footsteps. So thank you all. And I yield back.

Chairman BABIN. Yes, sir, very fascinating. Thank you.

Let's see. I now recognize the gentleman from Colorado, Mr. Perlmutter.

Mr. PERLMUTTER. Thanks. And I just love those questions Mr. Hultgren asked and your answers. I mean, this is like coming to super science class for me, and I'm so surprised by my colleague here, Ambassador Beyer, and all that he knows about science. You know, me, I watched Star Trek so I worry—I think about the next generation is a character, the traveler, so the time traveler or the Q Continuum, you know, all-powerful, whatever. Or Heinlein, you

know, talking about multi-dimensions and multi-universes so that you actually could be in a different time frame looking at our universe.

And I'm just so speechless by all of your testimony, and I just thank you for being here and I thank you for your optimism and your willingness to research and look into the future because that's what this is about.

So I'm just going to ask you a couple specific questions but you really have brightened my day and I thank you for that.

Space weather, let's—Dr. Ulvestad, let me—let's talk about space weather a little bit. I am working with Congressman Moolenaar and a couple of the Senators on space weather legislation. I guess my question is, we had Dr. Baker from University of Colorado—so I'm obviously from Colorado. And we've recently been assigned by the NSF, the National Solar Observatory, and we do a lot of space weather and space activities in Colorado. Can you tell us how space weather future looks?

Dr. ULVESTAD. So some of the members may know that we've recently developed national space weather strategy and a space weather action plan, and that was an interagency activity that involved NASA, NSF, not just the science research agencies but also people who might have to respond to space weather outbreaks and get early warnings out such as FEMA. So that, I think, was a really interesting process to develop this space weather strategy.

As part of the space weather strategy, NSF actually has some deliverables. So there's the long-term research aspects, and so I showed a picture of the Daniel K. Inouye Solar Telescope earlier. We're—really understanding the fundamental magnetic processes in the sun will be critical to us for eventually being able to predict space weather. I'm not going to guarantee that but understanding the sun means 10, 20, 30 years down the road we may be able to do better at that. And early warning systems enable satellites to shut down and point in the right direction and so on so they're not damaged.

Operationally, we right now run something called the Global Oscillations Network Group, which is run by the National Solar Observatory that, as you pointed out, is relocating to Boulder. And in our 2016 budget in our request we added money to make that a more robust system for predicting space weather. It's a network of six telescopes spread around the world so that it can, assuming it's not cloudy, observe the sun 24/7. And its data are actually used by the Air Force for operational space weather prediction.

So I think we have a mix of both an operational role where we're taking some of our research capabilities and transitioning them to operations and also the long-term research role.

Mr. PERLMUTTER. So I just spoke at a seminar and symposium on cybersecurity, and we were talking about electromagnetic pulses. So, you know, potentially manmade but more likely something coming out of the sun that—a flare of some sort that just fries, you know, our communications grid, our electrical grid, or whatever. So I hope—I mean, obviously, that's what you're talking in terms of the operational assistance that NSF is giving.

Dr. ULVESTAD. Yes, so the NSF role in that is primarily the research role. We don't have FEMA's job, and we don't have the DOE

job of sort of maintaining the electric grid. So our goal is to be able to produce the research that will enable us to do better predictions in the future, and the issue of like hardening the electric grid is kind of out of our realm.

Mr. PERLMUTTER. Just a closing thought—and, Dr. Hertz, I had a bunch of questions about this space shade that might help our telescopes—but I just want to congratulate the astronomers and the astrophysicists on—and somebody may have done this before I got here—on getting to Jupiter within one second and the engineers and the mathematicians and the technologists and everybody who helped on that. And my only question is how were we off by one second?

That was rhetorical. I'll yield back to the Chair.

Chairman BABIN. Thank you, Mr. Perlmutter.

And now, I recognize the gentleman from Ohio, Mr. Davidson.

Mr. DAVIDSON. Thank you, Mr. Chairman. Thank you all for being here. Thanks so much for the encouragement. And just an impressive amount of information.

Growing up near Dayton, Ohio, near Wright-Patterson Air Force Base, one of the first field trips I took was to the Neil Armstrong Space Museum as a kid. And so it's long been an interest. And I found that I would not be able to pilot any of these aircraft so I might just jump out of some of them so—here in our orbit, though.

So turning away from—not to take anything away from all the great science we've just talked about, I want to talk a little bit about the science of project management. And so, Dr. Hertz, you mentioned about the JWST program and for 2016 the goal was to have the three main components—the scientific instruments, the telescope, and the spacecraft—completed. Is that project on track?

Dr. HERTZ. The James Webb Space Telescope project is on track. It is executing the re-plan that was laid out in 2010 and for which Congress, thank you, has been appropriating the right amount of money in each year to allow us to make progress against that plan.

We have not accomplished the things that you listed, but those were not planned for 2016. In 2016 we've assembled the telescope and the instruments together, and the spacecraft is being assembled separately in California. The telescope and instruments are in Maryland. The spacecraft is in California. At the end of next year we will be shipping the telescope and instruments to California to be mated with the spacecraft.

Mr. DAVIDSON. Okay. Thank you.

Dr. HERTZ. But we are on plan with our—on track with our plan.

Mr. DAVIDSON. Okay. Thank you. Dr. Ulvestad, the telescope under construction in Maui, so thank you for the physical picture of it. It looks great, still in progress, but a bit over budget. Inspector General issued an alert warning for further cost and schedule risks to the project. I'm just curious what steps has NSF taken to address the concerns, and how confident are you that you will meet the new project deadline and budget?

Dr. ULVESTAD. So we're actually quite confident that we're on budget so that telescope was re-baselined to a new budget in 2013 because there was a two-year delay in access to the mountain due to environmental and cultural permitting issues in Hawaii.

So the Inspector General report made several recommendations. One of the concerns was the project schedule was working toward a completion in late 2019 but it was always known that that was the schedule without the risk associated. That was the schedule that had a six percent probability of being met. Okay. The schedule that had an 80 percent probability of being met was the middle of 2020, June of 2020. So we are quite confident that we're on schedule to meet that 80 percent date and actually to do it within our current baseline budget.

Mr. DAVIDSON. Great. Thank you. I have a question again, Dr. Hertz, or any others that want to comment. NASA's funding for large mission concept studies that will inform the 2020 National Academy of Sciences decadal survey, NASA anticipates that the survey committee will use these studies in formulating the recommendation for priorities of the missions following JWST and WFIRST. What does NASA intend to learn from these large-concept mission studies, and how may these studies influence the upcoming 2020 astronomy and astrophysics decadal study? Are these studies intended to influence the Academies' review process?

Dr. HERTZ. Thank you for that question. These studies are to put in front of the Decadal Survey Committee some options for prioritizing for missions that come in the next decade. So each of the study teams are made up of scientists drawn from across the country. Each of the studies will lay out a science case to lay out what amazing science could be done with that particular mission, to lay out a notional architecture, how big a telescope, what temperature, what orbit, what cameras, that sort of thing. And then we let the engineers take a look at it, and they'll estimate how long it would take to build and how much it might cost.

And that package that describes what such a mission might do and what kind of resources it might take, that can be put in front of the Decadal Survey Committee, and they can consider those as possible future missions or they can consider anything else they wish to consider as a possible future mission.

Mr. DAVIDSON. All right. Thank you. Mr. Chairman, I yield back.

Chairman BABIN. Thank you. Thank you very much. I want to thank the witnesses for their very valuable and fascinating testimony and for the members up here that have asked great questions.

The record will remain open for two weeks for additional comments and written questions from members.

And so with that, this hearing is adjourned.

[Whereupon, at 12:03 p.m., the subcommittees were adjourned.]

Appendix I

ANSWERS TO POST-HEARING QUESTIONS

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Responses by Dr. Paul Hertz

**HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON SPACE
SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY**

Astronomy, Astrophysics, and Astrobiology

Dr. Paul Hertz, Director, Astrophysics Division, Science Mission Directorate,
National Aeronautics and Space Administration

Questions submitted by Rep. Brian Babin, Chairman, Subcommittee on Space

QUESTION 1:

Please explain how the Arecibo Observatory is used by NASA for radio astronomy and Near-Earth Object (NEO) detection and characterization.

ANSWER 1:

NASA uses the Arecibo Observatory to characterize asteroids, and a few comets, to better determine their orbits and measure their size, shape, body dynamics, and surface features if they approach close enough to the Earth – but only after they have been initially detected by optical telescopes and the orbits have been established. The Arecibo radar is also used by NASA to map the surfaces of other planets to a level of detail not obtainable unless a spacecraft is sent to a low orbit around it. The surfaces of the inner planets (Mercury, Venus, and Mars), the Moon, and several of the moons of Jupiter and Saturn have all been mapped using the planetary radar capability of the Arecibo Observatory. Data from the radar were also used to determine the best surface locations for spacecraft landing on Mars. All of the asteroids that have been visited by spacecraft were first imaged by planetary radar, and Arecibo is currently being used to determine the best asteroid destination for the Asteroid Redirect Mission.

QUESTION 2:

How would the closure of Arecibo Observatory impact NASA's ability to conduct radio astronomy and Near-Earth Object detection and characterization?

ANSWER 2:

NASA has agreed with NSF to continue to fund the planetary radar capability at Arecibo for as long as they continue to operate it. If it is closed, NASA will continue to have planetary radar capability with its own Goldstone facility, a part of its Deep Space Network. However, the Goldstone Solar System Radar is not as powerful as Arecibo's so it will not have quite the same range into space as Arecibo. This means not as many NEOs can be characterized by radar as are currently done each year, but the number of NEO discoveries made each year would not change because this can only be done with optical telescopes, not radar.

QUESTION 3:

Arecibo Observatory obviously has a very illustrious history as a research facility, being the site of a lot of breakthroughs in radio astronomy. However, NSF funds several other newer radio astronomy facilities. Is Arecibo still a world-class facility or is it outclassed by sites like the Very Large Array in New Mexico? Does Arecibo have capabilities that are not found elsewhere? How would NASA's mission be impacted if NSF closed Arecibo?

ANSWER 3:

NSF's radio astronomy facilities have varied and complementary capabilities. The Arecibo 305-meter telescope and the Green Bank Telescope (GBT) in West Virginia are both single-dish reflectors. These telescopes excel in wide-area astronomical mapping of interstellar gas, and in cases where very fine resolution in frequency and/or timing are essential, such as pulsar observations or Solar System radar. NSF's other radio telescopes – the Very Large Array (VLA), the Atacama Large Millimeter/Submillimeter Array (ALMA), and the Very Long Baseline Array (VLBA) – are all interferometers, which generally provide high-resolution, frequency-specific images of small and/or distant radio-emitting objects. The radio receivers at Arecibo, GBT, VLA, and VLBA operate in overlapping parts of the spectrum, with Arecibo and GBT extending to the lowest frequencies; Arecibo is unique in being able to reach down to 50 megahertz (MHz). ALMA operates at higher frequencies, extending up to 950 gigahertz (GHz). The capabilities of Arecibo for radio astronomy and atmospheric science in general have been examined in the NSF Portfolio Review process, and discussed in the recent reports emanating from those studies, to which we defer.

With regard to radar observations, no NSF facility other than Arecibo is equipped with the powerful radar transmitter. However, the Green Bank Telescope (GBT) can receive returning radar signals that are transmitted from Arecibo or from NASA's antennas in California. The GBT can point anywhere above the local horizon while Arecibo's pointing ability is more limited, but as a receiving station it is currently only one-third as sensitive as Arecibo alone, and that is when Arecibo is used as the transmitter. Other radar-capable instruments, including NASA's telescopes at Goldstone, are even less sensitive, and NSF's interferometers (VLA, VLBA, and ALMA) are currently not used as radar receivers at all. So for radar observations of asteroids and other Solar System objects, Arecibo is not "outclassed" by newer facilities. Arecibo's higher sensitivity provides the capability to observe smaller and/or more distant objects than can be observed with other existing assets. In a recent study, a team of asteroid radar observation experts [Naidu et al. 2016, <http://arxiv.org/abs/1604.01080v2>] calculated how many known NEOs could have been observed by Arecibo and other facilities in 2015. They found that about 290 objects could have been seen by Arecibo, of which only 95 were in fact observed due to a combination of constraints including the observatory schedule, maintenance, weather, etc. In contrast, only about 131 objects could have been observed using NASA facilities alone, of which fewer than 39 actually were.

QUESTION 4:

How does the study of exoplanet atmospheres contribute to astrobiology and the search for life?

ANSWER 4:

Scientists are working to detect and characterize exoplanets (including their surfaces, interiors, and atmospheres) to determine the habitability of exoplanets and search for biosignatures. Using the past and present of Earth as a proxy, scientists think that certain combinations of atmospheric gases are likely due to the presence of life.

QUESTION 4a:

What chemical signatures in the atmosphere of an exoplanet would you consider sufficient to be clear proof of life on that planet?

ANSWER 4a:

This has yet to be conclusively determined by the science. There is not one single chemical signature of life. The best current signatures are those associated with production rates of chemicals that can only be explained by biological activity. The most well-studied examples would be oxygen and methane, in the presence of water vapor. We do not know how to maintain that combination of chemicals in an atmosphere without the high production rates of oxygen and methane associated with biology.

QUESTION 4b:

What chemical signatures in the atmosphere of an exoplanet would you consider to be necessary but not sufficient evidence for proof of life on that world?

ANSWER 4b:

There are no presumed necessary signatures, as different biospheres may produce different signals. Even our own planet likely exhibited different signatures over the history of biology on the planet. However, oxygen is likely to be included in any of our missions that plan to search for biosignatures because on modern Earth it is the easiest sign of life for us to detect. However, oxygen on its own is insufficient because we know of non-biological mechanisms through which oxygen can accumulate in an exoplanet atmosphere.

QUESTION 4c:

What other details about the development of life on other worlds may we be able to infer based on chemical signatures in those atmospheres?

ANSWER 4c:

Ultimately, any interpretation of a biosignature must be made against the background chemical inventory of the planet and within its environmental context. One of the fundamental lessons we have learned from our home planet is that life profoundly affects its environment, and the environment also profoundly affects any life that exists on it. So we will have a much better understanding of these interactions, and we will also have a better context through which to assess these interactions on Earth. For example, the scientific community is industriously considering atmospheric signatures for planetary processes like plate tectonics and volcanism that may be important to supporting life.

QUESTION 5:

How has the study of microbes living in deep sea vents and other harsh environments influenced how NASA conceives of and searches for life within our Solar System and beyond?

ANSWER 5:

Since Earth is the only known example of an inhabited planet, the search for life in the cosmos begins with our understanding of life on Earth. Studying the origins and evolution of life on Earth improves our ability to recognize and characterize life in its many forms. The study of organisms that thrive in physically or chemically extreme conditions shows us that life might be able to exist in a wide variety of locations throughout the universe.

QUESTION 6:

What do you see as the next major breakthrough for the search for life within our Solar System or beyond?

ANSWER 6:

Within our solar system, investigating the ocean worlds beyond earth would be a significant breakthrough. We suspect subsurface oceans in many of the outer planet satellites yet we know nothing about them, their depth, their volume, their chemical composition, etc.

Thanks to NASA's Kepler mission, we now know that planets are common and that planets that could harbor life are not rare in the universe. This means we can now design missions with the goal of finding signs of life on other worlds. We are studying two such missions in advance of the next decadal survey – an ultraviolet/visible/infrared surveyor, and a habitable exoplanet imaging mission.

QUESTION 7:

How have our observations of exoplanets thus far informed our general understanding of the numerical, size, and spatial distribution of planets around other stars?

ANSWER 7:

We now know that exoplanets are common, that most stars in our Galaxy are likely to have planetary systems, and that multi-planet systems like our solar system proliferate. We do not know how many of the stars in our Galaxy have potentially habitable planets in orbit around them, but some statistical methods estimate that value at 10 to 30 percent. The sizes of the exoplanets discovered so far range continuously from smaller than Mercury to super-Jupiters, and we now know that planetary systems can be packed much more tightly than was previously thought.

QUESTION 8:

To date, most exoplanets have been discovered using the transit method. Because the plane of a star system must be aligned almost perfectly edge-on for this to work, the transit method will only reveal a portion of the total population of exoplanets.

- a. What portion of observed stars are expected to line up with Earth so that the transit method will spot identify exoplanets?

ANSWER 8a:

The observability of planets when using the transit method depends on the size of the star and how close-in the planet orbits. The larger the star and the smaller the orbit, the greater the chance that a system will be aligned to produce an observable transit. For example, an observer randomly located outside our solar system would have a 1 in 85 chance of seeing Mercury transit, but only a 1 in 200 chance of seeing the Earth transit, and a 1 in 1100 chance of seeing Jupiter transit.

QUESTION 8b:

Based on observations so far, what can we infer about the broader population of exoplanets around other stars?

ANSWER 8b:

The first 15 years or so of exoplanet discovery were dominated by radial velocity measurements at ground based observatories. Because of the great success of NASA's Kepler mission, which launched in 2009, the transit technique is today the most prolific method for finding new exoplanetary systems. Since the transit technique is most sensitive to planets on small orbits, most of the more than 2300 confirmed exoplanets that Kepler has discovered have orbits the size of Earth's or smaller. As a result, we now know a great deal about the size distribution of planets from the habitable zone of their star inward. Most notably, we know that small planets are by far the most abundant: 80 percent of all confirmed Kepler planets have

a diameter of four times that of the earth or smaller.

We know less about the exoplanets that populate the region from the habitable zone outward. NASA looks forward to future missions such as the Wide Field Infrared Survey Telescope (WFIRST) that will use complementary techniques (gravitational microlensing, direct imaging) ideally suited to probing the outer regions of exoplanetary systems to complete our picture of planetary demographics.

QUESTION 8c:

What detection technologies are under development?

ANSWER 8c:

The five methods for detecting exoplanets in general use today are (1) the transit technique, (2) stellar radial velocity measurements, (3) gravitational microlensing; (4) astrometry, and (5) direct imaging. The first four of these techniques are all “indirect” detection methods, whereby the presence and nature of a planet is inferred by observing its effect on an observable star. The last, direct detection, is by far the most challenging, but also offers the greatest payoff—the ability to determine the characteristics and composition of exoplanet atmospheres and search for the signatures of life.

Direct detection and characterization of an Earth-twin exoplanet requires a technique for suppressing the overwhelming glare of a star so that the feeble reflected light from the planet—10 *billion* times fainter and lying incredibly close beside it—can be measured. NASA’s ongoing technology development activities in recent years have emphasized two different approaches for achieving such extreme starlight suppression: coronagraphs and starshades. Coronagraphs take in the light from a telescope and use advanced optical methods to block or cancel out the light from the star while allowing the light from planets to pass through to the detector. Starshades, on the other hand, are large, precisely contoured structures that are independent of the telescope and are positioned in front of it in such a way that the light from a star is blocked before it ever reaches the telescope while the light from any planets is unaffected. Both of these approaches are under study for use in future NASA missions.

QUESTION 9:

Our search for life within the Solar System (and our study of extremophiles on Earth itself) suggests that life may exist on moons or elsewhere outside of the traditional “habitable zone.” If there any way to estimate or bound the number of exoplanets that may harbor life outside of the habitable zone of another star?

ANSWER 9:

Because our past and current detection techniques are biased towards larger planets closer to their stars, and habitable-zone planets are smaller and further from their host stars, we cannot make an accurate estimate of the number of planets that are

within or beyond the habitable zone using direct observations. NASA's WFIRST mission is expected to provide us with the first estimates of the abundance of such planets because it will have a bias towards planets further from the host star, and a sensitivity to Earth-sized objects. However, a follow-up analysis of such worlds to search for signs of life would be extremely difficult. Because they are far from their stars, they will not reflect much starlight and will therefore be dim and extremely difficult to observe. They also will be unlikely to transit their host star – and the few cases that do transit will not transit often enough for us to accrue data on them. Finally, the signals from any biology on such a planet would be weak, as it is the combination of light from the host star interacting with nutrients in the ocean that has powered Earth's massive biosphere and generated strong signals detectable across interstellar space. Thus, the definition of the "habitable zone" is structured to focus our search on planets that – like Earth – have not only life but global biospheres capable of producing strong signals that are detectable across interstellar space.

We have no reason to suspect that a planet that is not in the habitable zone will sustain life. However, in our solar system there are moons that may sustain life even though they orbit planets that are outside of the habitable zone. Satellites (moons) that are habitable because they contain water but are not in the habitable zone cannot be detected with our current technologies and the scientific community has only suggested the possibility that they exist based on our own solar system. Furthermore, there have been no defensible estimates of their abundances because we still know too little about the structure of other planetary systems around other stars.

QUESTION 10:

In recent years, astronomers have discovered "rogue" planets that have been ejected from their original star systems. Could the moons of a large, Jupiter-sized rogue exoplanet (heated by tidal stresses, radioactive decay, or other mechanisms) harbor life?

ANSWER 10:

Yes, it is possible that life could exist on planets that do not orbit stars. But it would be difficult to test this hypothesis. We do not have any missions – or even known techniques – that could test whether or not such planets do harbor life.

QUESTION 11:

What existing telescopes and observatories are contributing to the characterization of exoplanets and evidence of habitability and what future telescopes will?

ANSWER 11:

NASA's Kepler, Spitzer, and Hubble Space Telescopes have each contributed to the characterization of exoplanets and the search for signs of life. The Transiting Exoplanet Survey Satellite (TESS), the James Webb Space Telescope, and the Wide

Field Infrared Survey Telescope will continue to extend this work over the next decade.

The Kepler mission makes use of the transit method to measure the sizes of exoplanets. TESS will do the same for a larger sample of stars spread across the whole sky and including the closest and brightest stars as seen from Earth. Ground based telescopes like the 10-m Keck I telescope and others operated by the European Southern Observatories make measurements of planet masses using the radial velocity technique. Hubble and Spitzer have characterized the atmospheres of a handful of “hot Jupiter” exoplanets, and JWST will extend those measurements to include a much larger number of even smaller planets. WFIRST will provide the capability to directly image and characterize cool/giant exoplanets similar to Jupiter and Saturn with orbits a few times larger than the Earth’s orbital distance.

QUESTION 11a:

How will the James Webb Space Telescope be used to study exoplanets?

ANSWER 11a:

The James Webb Space Telescope will measure the spectrum of the starlight filtering through the atmosphere of a transiting exoplanet to determine the composition of that planet’s atmosphere. It will also carry a coronagraph to enable direct imaging of large exoplanets on wide orbits in relatively young exoplanetary systems where the planets are still glowing from the heat of their formation.

QUESTION 11b:

How will the Transiting Exoplanet Survey Satellite be used to study exoplanets?

ANSWER 11b:

TESS is designed to survey the brightest and nearest stars spread across the whole sky, and is expected to discover thousands of exoplanets. In its two-year survey of the solar neighborhood, TESS will monitor more than 200,000 stars for temporary drops in brightness caused by planetary transits. Because of their close proximity to Earth, the planetary systems that TESS finds will be the most attractive targets for JWST exoplanet characterization observations and a future direct exoplanet detection and characterization mission.

QUESTION 11c:

How will the Wide-Field InfraRed Survey Telescope be used to study exoplanets?

ANSWER 11c:

WFIRST will search for exoplanets by watching for gravitational microlensing events occurring against the distant backdrop of the Milky Way’s halo stars. When a foreground star happens to pass in front of a halo star, its gravity bends the light of

the background star, focusing it slightly and making it appear to brighten. If the foreground star has a planet in orbit around it, the planet's (much weaker) gravitation will give rise to a "blip" on the light curve of the event. Since gravitational microlensing is sensitive to planets as small as Earth on orbits the size of a star's habitable zone and larger, the WFIRST microlensing exoplanet survey will perfectly complement the Kepler survey, completing the picture of the demographics of exoplanetary systems. It is predicted that WFIRST will discover about 2600 exoplanets in this way.

In addition, the Coronagraph Instrument aboard WFIRST will also perform high contrast imaging and spectroscopy of dozens of Jupiter- and Saturn-sized gas giants in nearby planetary systems in order to measure the molecular constituents within their atmospheres.

QUESTION 12:

How much of NASA's current astrobiology program focuses on the study and characterization of exoplanets?

ANSWER 12:

Currently, NASA's Astrobiology Program and Planetary Science Division invests close to \$12 million a year on characterizing exoplanets.

QUESTION 12a:

How much of that research is dedicated to spectroscopy and the identification of biosignatures in the atmospheres of those planets?

ANSWER 12a:

About \$3 to \$4 million focuses specifically on understanding biosignatures that could be detected via spectroscopy.

QUESTION 12b:

Is the Habitable Exoplanets Catalog at the University of Puerto Rico at Arecibo considered the authoritative catalog of exoplanets that can theoretically support surface life?

ANSWER 12b:

No, the research community does not consider the Habitable Exoplanets Catalog (known as the PHL) at the University of Puerto Rico at Arecibo to be an authoritative catalog of exoplanets that can theoretically support surface life. There is no authoritative site because that would require the formation of a catalogue that is actively peer reviewed by the science community. However, the PHL Catalog has been a wonderful resource for public outreach with respect to exoplanet habitability because of its accessibility. The NASA Exoplanet Archive

(<http://exoplanetarchive.ipac.caltech.edu/>) catalogs data on all exoplanets and exoplanet candidates, including small, rocky exoplanets in the habitable zone.

QUESTION 13:

The scientific community has made great strides in the search for life elsewhere within our Solar System. Is there any sort of catalog, or index of locations that are thought to potentially harbor life or are considered likely to harbor life?

ANSWER 13:

There is no such catalog. However, good candidates for environments that might be able to support life similar to that found on Earth include Mars, and the icy satellites Europa, Enceladus. It is also possible that any other bodies in our solar system that have liquid water or even liquid hydrocarbons, like Titan, could support life.

QUESTION 14:

Our observations of the solar system seem to have conclusively ruled out, in some cases, some kinds of life. Is there an inventory or list of places within the solar system where the presence of life (or at least organisms of a certain size) has been disproven? How could these determinations change based upon new science?

ANSWER 14:

No, to our knowledge there is no catalog of places that have conclusively ruled out life. However, there are places in our solar system that scientists think are unlikely to support life as we know it, such as Mercury, the surface of Venus, and the gas giants, Saturn and Jupiter.

QUESTION 15:

What are the most important technological advancements that are needed to further astrophysics research? What advancements should be our highest priority?

ANSWER 15:

Continued breakthroughs in astrophysics research hinge on detecting ever fainter sources of electromagnetic radiation throughout the spectrum, detecting minute perturbations of the space-time continuum caused by gravitational waves, and developing high-contrast imaging systems to observe exoplanets.

Detection of gravitational waves from a space-based observatory is listed as a high priority in the 2010 Decadal Survey, and this assessment was recently reinforced by the midterm assessment of the Decadal Review. High-contrast imaging is also a high priority according to the 2010 Decadal Survey. A coronagraph is currently under development as a technology demonstration instrument on the WFIRST mission, scheduled to launch in the middle of the next decade, making this

coronagraph instrument a relatively high technology development priority within the Astrophysics Division.

QUESTION 16:

The Neutron Star Interior Composition Explorer Mission (NICER), launching in August, is the next mission in NASA's Explorers Program. Can you explain the research goals of NICER, as well as how they fit into the goals of the Explorers Program as a whole?

ANSWER 16:

NICER is an International Space Station (ISS) payload devoted to the study of neutron stars through soft X-ray timing. NICER will also have a robust Guest Observer program aimed at studying a broad variety of astrophysics sources, from stellar mass black holes to active galaxies. In addition to its science goals, NICER will enable the first space demonstration of pulsar-based navigation of spacecraft, through the Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) enhancement to the mission. NICER will enable focused, compelling science utilizing an innovative approach and for a modest cost – one of the goals of the Explorers program.

QUESTION 17:

Two important upcoming NASA missions, TESS and WFIRST, focus on studying exoplanets. What are the recent breakthroughs and discoveries in exoplanet research that these two missions will be building upon? What do these missions plan to accomplish in addition to finding more exoplanets?

ANSWER 17:

NASA's Kepler mission has been a resounding success, providing our first detailed census of the abundance, sizes, and orbits of planets in our galaxy. In addition, exciting new exoplanets are discovered almost daily, planets like the recently announced Proxima Centauri b—an Earth-sized planet in a potentially habitable orbit around the closest star to our solar system, just 4.2 light years away. TESS will build on this work by conducting an all-sky survey of the closest and brightest stars, revealing the planets in our own "neck of the woods." In doing so, TESS will identify the most interesting exoplanets in the solar neighborhood for other telescopes to characterize more thoroughly.

WFIRST's microlensing planet survey will reveal the demographics of planetary systems beyond the habitable zone, thereby completing census of planetary systems begun by Kepler. The WFIRST coronagraph instrument is being designed to directly image and make spectral measurements of nearby gas giant planets found by the radial velocity technique. As a result, it will provide direct measurements of the composition and characteristics of those planets, as well as (likely) discovering new ones.

In addition to studying exoplanets, WFIRST will settle essential questions in the areas of dark energy and infrared astrophysics.

QUESTION 18:

In 2013, NASA started two mission concept studies investigating new technologies that could detect exoplanets around nearby stars. The results were published in March 2015 and detailed two potential spacecraft that NASA could build. How close does TESS come to fulfilling the vision of either of these concept studies?

ANSWER 18:

The TESS mission concept pre-dates those two studies and has no connection to them. TESS is designed to conduct an all-sky survey for transiting planets, while the two mission concept studies focused on exoplanet direct imaging. Essentially, TESS will provide exoplanet targets that a mission such as those described in the concept studies could follow up on and characterize.

QUESTION 19:

Researchers are testing designs for a starshade, which would fly in formation with WFIRST. The starshade, also known as an "external occulter," would block the light from a star while allowing the telescope to spot emissions from much dimmer orbiting planets. Such technology may enable spectra to be examined of some planets located in the "habitable zone" around their stars, where liquid water could exist on a world's surface. How is NASA using the funding provided by Congress to study the development of a starshade for WFIRST? When does NASA intend on making a decision whether to include a starshade with WFIRST?

ANSWER 19:

NASA is studying the cost of adding design features to WFIRST to ensure compatibility with current starshade design concepts, and will quantify the additional cost and risk that WFIRST would incur by implementing these design features. Within the next year, NASA expects to make a final decision on WFIRST starshade compatibility based on an assessment of the scientific benefits versus the additional risk and cost.

During the current fiscal year, NASA is investing in starshade technologies. NASA is following a technology roadmap that would enable starshades to achieve maturity for use with future space telescopes, potentially in time for a launch while WFIRST is operational.

In considering whether to develop an actual starshade for flight with WFIRST, NASA will follow the same process as for other strategic science flight projects. NASA will factor the recommendations of the National Academy of Sciences' next Decadal Study of Astronomy and Astrophysics into any decision on a starshade mission.

QUESTION 20:

You recently established mission concept studies for several large astrophysics survey missions. These missions would interrogate various electromagnetic spectra to examine our universe, and are reminiscent of NASA's Four Great Observatories program. Given our current capabilities, and also the improvements that will accompany upcoming missions such as James Webb Space Telescope (JWST), what are the criteria NASA is using to assess which of these four mission concepts would offer the greatest improvement to our existing astrophysics program?

ANSWER 20:

NASA initiated these concept studies to inform the 2020 Decadal Survey process conducted by the National Academies. NASA anticipates that the Decadal Survey Committee will use these studies in formulating their recommendation for the priorities for NASA's large strategic missions following JWST and WFIRST. The goal is to present to the Decadal Committee four compelling and executable mission concepts. We await the committee's assessment of the science benefit of each of these concepts.

QUESTION 21:

In theory, could planets with a sufficiently large mass be detected and studied using gravitational waves?

ANSWER 21:

No. The study of gravitational waves will not result in the detection or characterization of exoplanets.

QUESTION 22:

Please provide any perspectives you may have on KIC 8462852, commonly known as the "Tabby Star."

ANSWER 22:

This star has dense, irregular clouds of material orbiting it and is still the subject of active research. It is an outstanding example of new science enabled by extending Kepler into the K2 mission.

QUESTION 23:

Please provide your perspectives on the Association of University's for Research in Astronomy (AURA) proposal for a High-Definition Space Telescope (HDST).

ANSWER 23:

There have been several studies of large space telescopes capable of directly detecting habitable exoplanets in order to conduct a survey for biosignatures; such a space telescope could also address compelling questions in cosmology and the evolution of structure in the universe. The High-Definition Space Telescope study sponsored by AURA was one such study. A future mission of this kind is featured prominently in NASA's astrophysics roadmap ("Enduring Quests, Daring Visions," <http://science.nasa.gov/science-committee/subcommittees/nac-astrophysics-subcommittee/astrophysics-roadmap/>) and is currently being studied by NASA, under the name Large Ultraviolet/Optical/Infrared (LUVOIR) Surveyor, for submission to the 2020 Decadal Survey.

**HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON SPACE
SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY**

Astronomy, Astrophysics, and Astrobiology

Dr. Paul Hertz, Director, Astrophysics Division, Science Mission Directorate,
National Aeronautics and Space Administration

Questions submitted by Rep. Dana Rohrabacher

QUESTION 1:

Dr. Hertz, what NASA work has been performed at Arecibo Observatory over the past three years? Would that work have been better performed elsewhere?

ANSWER 1:

NASA observed about 100 asteroids in both 2014 and 2015 using radar techniques from radio observatories, and has continued to make these observations over the past year. Arecibo observed about 85 percent of them, and about 65 percent were observed by Arecibo alone. Asteroid Bennu, soon to be visited by OSIRIS-REx, was imaged by this planetary radar, and Arecibo is currently being used to determine the best asteroid destination for the Asteroid Redirect Mission. While many of these observations could have been made with NASA's own Goldstone Solar System Radar, no other facility has Arecibo's sensitivity and range to observe near-Earth asteroids.

QUESTION 2:

Dr. Hertz, the Goldstone Solar System Radar is a facility with great capabilities, especially in communicating with our deep space missions. Can you provide greater clarity about how the capabilities of the Arecibo Observatory compare with Goldstone with regard to important NEO tracking and characterization parameters:

- a. Sensitivity?

ANSWER 2a:

The Arecibo radar system is about 15 times more sensitive than that at Goldstone, when compared in the same transmit-and-receive (monostatic) mode. This difference is due to both the higher transmitter power and the larger antenna size at Arecibo.

QUESTION 2b:

Maximum resolution for imaging?

ANSWER 2b:

Both Arecibo and the 70-meter DSS-14 antenna at Goldstone have the same recent transmitter upgrades to allow radar imaging of features down to four meters in size when the observing conditions are good. The smaller DSS-13 telescope can achieve resolution about four times finer if used as a transmitter with Arecibo or the Green Bank Telescope (GBT) as a receiver (i.e. bi-static radar mode), albeit with far lower sensitivity (i.e. this setup does not have as great of range).

QUESTION 2c:

Maximum distance for observation?

ANSWER 2c:

Asteroids must pass within about 20 million miles of the Earth to be observable by either of these ground-based radars. The actual distance that a specific asteroid can be observed depends on its size and other observability factors such as composition and rotation speed. Arecibo is able to observe smaller asteroids at a greater distance. Very roughly speaking, if all other factors are equal, Arecibo can detect a given asteroid about twice as far away as can Goldstone.

QUESTION 2d:

Percentage of time available for astronomy observations?

ANSWER 2d:

In 2015, the telescope was used for radar observations about 5 percent of the total time, and for other types of astronomical research about 44 percent of the time. At Goldstone, approximately 6 percent of the total time has been used for radar observations, and about 10 percent for other kinds of astronomical observations. All of these percentages are relative to the total number of hours ($365 \times 24 = 8,760$) in a year, and do not take into account the fraction of time either telescope is down for engineering, maintenance, weather, or other reasons.

QUESTION 2e:

Availability for short-notice, target-of-opportunity observing requests?

ANSWER 2e:

Arecibo can be made available for short-notice, target-of-opportunity radar observing requests within hours; a comparable request at Goldstone takes typically about two days because of its proximity to air corridors and military ranges. But in either case, the ability to observe a newly discovered asteroid is driven more by how quickly a sufficiently accurate orbit for doing radar observations can be derived from optical telescope observations. Radar cannot be performed until it can be accurately pointed and the round trip signal time determined.

QUESTION 3:

Dr. Hertz, you mentioned that unlike Goldstone, "Arecibo cannot be moved, sitting in a valley the way it does." That leaves the impression that Arecibo can only see a very limited number of NEOs. What percentage of NEOs pass within the field of view, and thus are observable, from the Arecibo Observatory?

ANSWER 3:

Arecibo has limited steerability through movement of its secondary antenna (the equipment suspended above the main dish antenna), but only about 30 percent of the sky is observable by Arecibo, while Goldstone's fully steerable radio antenna can observe about 80 percent of the sky. Even so, as of the end of 2015 Arecibo was capable of observing almost 75 percent more of the known near-Earth asteroids (NEAs) (430 for Arecibo versus 246 for Goldstone) due to its greater range and sensitivity in the sky accessible to its antenna, but this is only about 3 percent of the known catalogue because the range of even Arecibo is limited to only about 20 million miles from the Earth.

**HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON SPACE
SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY**

Astronomy, Astrophysics, and Astrobiology

Dr. Paul Hertz, Director, Astrophysics Division, Science Mission Directorate,
National Aeronautics and Space Administration

Questions submitted by Rep. Donna Edwards, Ranking Member,
Subcommittee on Space

QUESTION 1:

The Kepler mission has identified a population of extra-solar planets that future missions, such as the James Webb Space Telescope and the Transiting Exoplanet Survey Satellite (TESS), can explore in more detail. Do we have the technologies—the telescopes and the instruments to do the spectral analysis to search for biosignatures in the atmospheres of habitable exoplanets?

ANSWER 1:

The James Webb Space Telescope will be able to measure the spectrum of the starlight filtering through the atmosphere of many transiting exoplanets discovered by TESS, and to use those measurements to infer the gross composition of the planet's atmosphere. It is possible that the list may include some candidate habitable planets, but it will require some luck (i.e. a very nearby system). However, even if such targets are available, it is not clear that transit spectroscopy will be able to provide sufficient spectral detail to allow biosignature detection. Future space telescopes, specifically designed to strongly suppress the light of the host stars and directly analyze the light from the planets around it, will be needed if there is to be a broad-based search for biosignatures in nearby habitable planets.

QUESTION 1a:

If not, is NASA currently investing in technologies that will enable this research?

ANSWER 1a:

Yes. NASA has been investing in the needed technologies for almost 2 decades. But it is extremely challenging because of the enormous disparity in brightness between a star and the brightness of any planets in orbit around it. Direct detection and characterization of an Earth-twin exoplanet requires a technique for suppressing the overwhelming glare of a star so that the feeble reflected light from the planet—10 *billion* times fainter and lying incredibly close beside it—can be measured. NASA's ongoing technology development activities in recent years have emphasized two different approaches for achieving such extreme starlight suppression: coronagraphs and starshades. Coronagraphs take in the light from a telescope and use advanced optical methods to block or cancel out the light from the star while

allowing the light from planets to pass through to the detector. Starshades, on the other hand, are large, precisely contoured structures that are independent of the telescope and are positioned in front of it in such a way that the light from a star is blocked before it ever reaches the telescope while the light from any planets is unaffected. Both of these approaches are under study for use in future NASA missions.

QUESTION 1b:

When do you expect this capability to be available to scientists?

ANSWER 1b:

NASA's Exoplanet Exploration Program is pursuing a technology development plan that is designed to bring both coronagraphs and starshades to a level of technology readiness suitable for inclusion in a new flight mission that could follow WFIRST.

QUESTION 2:

In your prepared statement you discuss NASA's plans to initiate studies for potential medium-sized Astrophysics Probe missions. How would the medium-sized Probe missions differ from the small and medium-sized Explorer Program missions?

ANSWER 2:

Astrophysics Probes missions are envisioned to have a total lifecycle cost greater than that of a small- or medium-sized Explorer Program mission and less than approximately \$1 billion.

QUESTION 2a:

Where is NASA in the process of studying the probe missions?

ANSWER 2a:

NASA is soliciting concept studies from the community now.

QUESTION 2b:

When can we expect NASA to announce an opportunity for astronomers to propose their ideas?

ANSWER 2b:

NASA released ROSES-16 Amendment D.12 "Astrophysics probe mission concept studies" on August 17, 2016.

QUESTION 3:

What needs to be done to improve the decadal survey process for estimating the development cost of large-scale facilities and missions?

ANSWER 3:

The National Academies of Sciences, Engineering and Medicine, in their 2015 report, *The Space Science Decadal Surveys; Lessons Learned and Best Practices*, details the cost and technical evaluation (CATE) process utilized during the 2010 Decadal Survey, including its limitations and suggested best practices. One lesson learned is that reference missions should be developed to determine if there is a way to do the science within a certain cost range, rather than as a detailed recommendation for implementation requiring a full and detailed costing exercise.

QUESTION 3a:

Please describe the cost-estimate analysis being conducted by the ongoing large-scale mission concept studies for the 2020 decadal survey. How does the process for estimating the costs of the mission concepts compare to the cost estimating process used for the New Worlds, New Horizons in Astronomy and Astrophysics decadal survey?

ANSWER 3a:

The concept study teams will utilize standard practices and cost models for estimating mission cost at the mission concept level of maturity. NASA has set aside modest funding for the Aerospace Corporation to advise the study teams on cost and risk implications of their mission architecture, to help identify areas for deeper engineering, and areas where rules of thumb can suffice. At the conclusion of the concept study period, and prior to submitting the studies to the 2020 Decadal Survey Committee, NASA will conduct an independent cost assessment of the large mission concept studies.

QUESTION 4:

In your prepared statement, you mention that NASA is exploring partnerships with a number of space agencies for the WFIRST observatory? What partnerships are being explored and when do you expect decisions to be made regarding potential partnerships?

ANSWER 4:

NASA has had conversations with the European Space Agency (ESA), Canadian Space Agency (CSA), Japanese Aerospace Exploration Agency (JAXA), and Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) regarding potential contributions to WFIRST. In evaluating partnership options, NASA is giving priority to contributions that utilize any unique capabilities of potential partner nations, so as not to deny opportunities to US industry. NASA's

evaluation of partnership options will also consider the degree of cost savings that these options provide to the US taxpayer. NASA expects to initiate official international agreements before the mission proceeds to Phase B in October 2017.

QUESTION 5:

Please describe NASA's ongoing efforts to mature the star shade technology that could potentially accompany the WFIRST mission. What are the science benefits of such a star shade and how do they align with the decadal survey priorities? Does the addition of a star shade introduce additional risks? If so, what are they?

ANSWER 5:

The National Academy of Sciences' 2010 Decadal Study of Astronomy and Astrophysics identified the New Worlds Technology Program as its top medium-scale space project. The report identified exoplanet science as "one of the fastest growing and most exciting fields in astrophysics," and called upon NASA to develop "candidate starlight suppression techniques." NASA is investing in two starlight suppression techniques, i.e. coronagraphs and starshades, and these two techniques have different capabilities. Starshades can observe over a wide range of angles, and can adapt to a variety of different telescope designs. Coronagraphs, on the other hand, provide high observational efficiency, and are maturing rapidly as a technology. On a mission such as WFIRST, starshades and coronagraphs would complement each other due to the unique capabilities of each technique.

During the current fiscal year, NASA is investing in starshade technologies. NASA is following a technology roadmap that would enable starshades to achieve maturity for use with future space telescopes, potentially in time for a launch while WFIRST is operational.

NASA is incorporating design features into WFIRST to ensure compatibility with current starshade design concepts. NASA will quantify the additional cost and risk that WFIRST incurs by implementing these design features. Within the next year, NASA expects to make a final decision on WFIRST starshade compatibility based on an assessment of the scientific benefits versus the additional risk and cost.

QUESTION 5a:

How will a decision on the potential addition of a star shade be made?

ANSWER 5a:

In considering whether to develop an actual starshade for flight with WFIRST, NASA will follow the same process as for other strategic science flight projects. NASA will factor the recommendations of the National Academy of Sciences' next Decadal Study of Astronomy and Astrophysics into any decision on a starshade mission.

Responses by Dr. Jim Ulvestad

**Astronomy, Astrophysics, and Astrobiology
Response to Questions For the Record
Dr. James S. Ulvestad, Division Director
Division of Astronomical Sciences (AST)
National Science Foundation
September 2, 2016**

Questions submitted by Rep. Brian Babin, Chairman, Subcommittee on Space

1. *When do you expect to know if you will be mothballing Arecibo? What is influencing the decision? You said in your testimony that you are considering a variety of options? What do these options entail and how would each one influence U.S. research capabilities?*

The scientific rationale for NSF to reduce funding for the Arecibo Observatory has been established through a number of reviews and surveys conducted by the science community. In 2010, the National Academies concluded their sixth decadal survey in astronomy and astrophysics. In their report, *New Worlds, New Horizons in Astronomy and Astrophysics*¹, the National Academies committee recommended that: “NSF-Astronomy should complete its next senior review before the mid-decade independent review that is recommended in this report, so as to determine which, if any, facilities NSF-AST should cease to support in order to release funds for (1) the construction and ongoing operation of new telescopes and instruments and (2) the science analysis needed to capitalize on the results from existing and future facilities.”

In response to this recommendation, the NSF Directorate for Mathematical and Physical Sciences (MPS) commissioned a subcommittee of the MPS Advisory Committee to assess the portfolio of the Division of Astronomical Sciences (AST). This subcommittee, composed solely of external members of the scientific community, was charged with recommending a balanced portfolio to maximize the science recommended by National Academies decadal surveys, under constrained budget scenarios. The resulting Portfolio Review Committee Report (PRC Report) was released in August 2012². It recommended divestment of a number of telescopes from the federal portfolio in order to maintain a balance of small-, medium-, and large-scale programs that would best address decadal survey science. With respect to Arecibo Observatory, the PRC Report made the following recommendation (Recommendation 10.4): “AST should reevaluate its participation in Arecibo and SOAR later in the decade in light of the science opportunities and budget forecasts at that time.” This follows from a recommendation made by the AST Senior Review in 2006³ (Recommendation 6): “The National Astronomy and Ionosphere Center [former name for Arecibo Observatory]...should seek partners who will contribute personnel or financial support to the operation of Arecibo...by 2011 or else these facilities should be closed.”

¹ <https://www.nap.edu/catalog/12951/new-worlds-new-horizons-in-astronomy-and-astrophysics>

² www.nsf.gov/mps/ast/ast_portfolio_review.jsp

³ www.nsf.gov/mps/ast/seniorreview/sr_report_mpsac_updated_12-1-06.pdf

The Senior Review Report also noted that “If Arecibo is kept operating beyond 2011, it is expected that this will only be a limited-term extension, pending the deliberations of the next decadal survey.”

While AST was the primary Arecibo funder in NSF for over a decade, the Geospace Section (GS) of the NSF Division of Atmospheric and Geospace Sciences in the Directorate for Geosciences (GEO) was an early co-funder of Arecibo Observatory operations and now provides approximately half of the current NSF funding (\$4.1 million annually from GS) for Arecibo. In 2016, a subcommittee of the GEO Advisory Committee concluded its own community-based portfolio review, which recommended a significant and specific funding reduction. The GEO report⁴ stated (Recommendation 9.11): “The GS should reduce its M&O [Management and Operations] support for the Arecibo Observatory (AO) to \$1.1M by 2020, i.e., to a proportional pro rata level approximately commensurate with its fractional NSF GS proposal pressure and usage for frontier research.”

The continued importance of the NSF response to the PRC Report was highlighted by the annual report of the Congressionally chartered Astronomy and Astrophysics Advisory Committee in March 2016⁵, which recommended that “[s]trong efforts by NSF for facility divestment should continue as fast as is possible.” More recently, in August 2016, the National Academies mid-decadal report, “New Worlds, New Horizons. A Midterm Assessment,”⁶ provided their Recommendation 3-1: “The National Science Foundation (NSF) should proceed with divestment from ground-based facilities which have a lower scientific impact, implementing the recommendations of the NSF Portfolio Review, that is essential to sustaining the scientific vitality of the U.S. ground-based astronomy program as new facilities come into operation.”

The process currently being carried out by NSF is responsive to three primary statutes: the National Environmental Policy Act (NEPA), the National Historic Preservation Act (NHPA), and the Endangered Species Act (ESA). The Environmental Impact Statement (EIS) process is established under NEPA, and is being carried out concurrently with compliance with Section 106 of NHPA and Section 7 of ESA.

For NEPA, the EIS process includes public scoping meetings to discuss preliminary proposed alternatives and any considerations regarding the scope of the environmental analysis that the public wishes to bring to NSF’s attention. The scoping process for the Arecibo EIS will be followed by publication of a Draft EIS in the autumn of 2016, again accompanied by public hearings and comments. NSF then will prepare a Final EIS, with a target publication date in the spring of 2017. In July 2016, NASA indicated its wish to be a cooperating agency in preparation of the EIS,

⁴ www.nsf.gov/geo/adgeo/geospace-review/geospace-portfolio-review-final-rpt-2016.pdf

⁵ www.nsf.gov/mps/ast/aaac/reports/annual/AAAC_2015-16_Report.pdf

⁶ <https://www.nap.edu/catalog/23560/new-worlds-new-horizons-a-midterm-assessment>

so NASA will be fully engaged in the EIS activities.

The preliminary proposed alternatives for the EIS process are listed below, but it is important to note that these may be changed based on public input and new information that is learned throughout the process:

- Alternative 1: Collaboration with Interested Parties for Continued Science-focused Operations
- Alternative 2: Collaboration with Interested Parties for Transition to Education-focused Operations
- Alternative 3: Mothballing of Facilities
- Alternative 4: Partial Deconstruction and Site Restoration
- Alternative 5: Full Deconstruction and Site Restoration
- No-Action Alternative: Continued NSF Investment for Science-focused Operations

Concurrently, the NHPA process involves consultation with the State Historic Preservation Officer (SHPO) and the public, identification of historic properties, assessment of possible adverse effects, and (if necessary) resolution of adverse effects. Consultation with the SHPO and the Advisory Council for Historic Preservation has already begun and will continue throughout the process.

The ESA prohibits actions likely to jeopardize the existence of listed species. As required under Section 7 of the ESA, NSF has begun consultation with the U.S. Fish and Wildlife Service regarding any listed species that could be affected by any of the possible alternatives for operational changes at Arecibo Observatory.

The outcome of all the processes above, plus additional programmatic (e.g., budgetary, risk, and scientific considerations) will result in a Record of Decision to be issued by NSF. That Record of Decision will include a selected alternative and will be accompanied by any mitigation measures deemed necessary to carry out that alternative. NSF currently is targeting the summer of 2017 for this Record of Decision. NSF is committed to an open process and full consideration of any issues that are identified during the actions described above, so the target date could slip if additional work is required to address new issues that arise. Following issuance of the Record of Decision, NSF will proceed to carry out its implementation on a timeline that is consistent with the choices made in the Record of Decision, the availability of funds, and any other programmatic or legal considerations that must be put in place before implementation.

Of the preliminary proposed alternatives listed above, Alternative 1 and the No-Action Alternative would likely have little impact on U.S. research capabilities; for Alternative 1, this depends to some degree on the nature of the science-focused collaboration. For Alternatives 2, 3, 4, and 5, the 305-meter radio telescope at

Arecibo would cease to be operational. Many of its radar capabilities also exist at the 70-m Goldstone antenna of NASA's Deep Space Network. Many of the other radio astronomy capabilities exist at the 100-meter Robert C. Byrd Green Bank Telescope (GBT) in West Virginia and at the Very Large Array (VLA) in New Mexico. Both of these radio observing systems have an all-sky pointing capability and an extensive range of observing frequencies that are not achievable with the lower-precision reflector at Arecibo.

Alternative 3 identified above, for mothballing of the facility, would not be a permanent loss of Arecibo's capabilities. If a collaboration with interested parties were established while the 305-meter telescope was mothballed, the research capabilities could be restored.

2. *If Arecibo were shut down, what capabilities would we lose? You said in your testimony that the Goldstone observatory has similar capabilities in terms of asteroid characterization, but that Arecibo is able to characterize more distant asteroids. What are the differences in capabilities between Goldstone and Arecibo?*

The Goldstone Solar System Radar is installed on NASA's 70-meter antenna of its Deep Space Network, near Barstow, California. Because the Goldstone radar is a NASA capability and not an NSF facility, we do not have first-hand knowledge of Goldstone's characteristics. Instead, for Goldstone, we rely on a paper on radar capabilities, soon to be published in the *Astronomical Journal*, that may be found at <http://arxiv.org/abs/1604.01080>.

The Goldstone radar is a factor of two less powerful than the Arecibo radar (450 kilowatts at Goldstone vs. 900 kilowatts at Arecibo); combining this power with the size of the dishes means that the Arecibo radar is about 15 times more sensitive. The exact comparison of capabilities depends on the nature of the asteroid being targeted by the radar. However, since radar return generally depends on the fourth power of the distance to an illuminated object, the factor of 15 in sensitivity would mean that the Arecibo radar could illuminate and detect (at similar signal-to-noise level) asteroids that are about twice as far away as the Goldstone radar. In a configuration that uses radar transmission from Goldstone and radar reception by the Robert C. Byrd Green Bank Telescope, Goldstone can transmit all the time, rather than having to turn off the transmission in order to receive the radar return. In that case, the advantage of the stand-alone Arecibo capability would be reduced by more than a factor of two.

The Goldstone 70-meter dish also has the capability of using its radar in the entire sky visible from its location in California, down to an elevation limit of 20 degrees above the horizon, while Arecibo is limited to point to directions only more than 70 degrees from the horizon (also described as within 20 degrees of the zenith, straight overhead).

Goldstone capabilities, like Arecibo capabilities, are limited by available funding and priorities. As much as 28 years ago, NASA and the Jet Propulsion Laboratory were

discussing upgrades to the Goldstone radar to double its power, which would make Goldstone slightly more competitive with Arecibo (see <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19890000838.pdf>). To date, NASA has not implemented an upgrade of the Goldstone power. Goldstone also spends substantial amounts of its time tracking interplanetary spacecraft; the priority of that tracking activity compared to the planetary radar usage is determined by NASA, not by NSF.

For further, quantitative comparisons of planetary radar capabilities, we suggest contacting the NASA Planetary Defense Coordination Office.

3. *As NSF considers the future of Arecibo Observatory, how is the Foundation working with other agencies and Departments such as NASA or the Department of Defense, to assess their interest in using the facility as a continued federal asset? What would the barriers be to transferring the facility to another federal entity?*

The NSF has worked closely with both NASA and the Department of Defense to assess interest in utilizing Arecibo Observatory as a continued federal asset. In FY2016, NASA contributed approximately \$3.6M to the Arecibo Observatory budget, specifically for solar system radar observations. The NSF has conducted discussions directly with the Director of NASA's Planetary Science Division (PSD) regarding interest by the NASA Planetary Defense Coordination Office in continuing to utilize Arecibo Observatory as a federal entity. As a result of these discussions, in April 2016 NSF received a letter from the Director of NASA's PSD stating that PSD would plan to continue to utilize Arecibo Observatory in a similar manner and at a similar level of support, and would be willing to cooperate with NSF during any management transition.

The NSF has worked directly with the Department of Defense (DoD) to assess possible interest in utilization of Arecibo Observatory as a continued federal asset. The limited pointing capabilities of the Arecibo 305 meter facility (the telescope can observe objects only within 20 degrees of the zenith) make the telescope less useful for some DoD programs. However, on-going discussions are focusing on DoD programs that are less sensitive to the telescope's pointing considerations.

The NSF co-chairs the Astronomical Assets and Data (AAD) Interagency Working Group, a working group of the National Science and Technology Council's Committee on Homeland and National Security. The AAD, made up of a broad cross section of federal agencies, is regularly briefed on the status of NSF astronomical facilities recommended for divestment, including Arecibo Observatory.

With regard to transferring Arecibo Observatory to another federal entity, the NSF holds statutory authority to transfer the title of the facility directly to another federal entity.

4. *Arecibo Observatory obviously has a very illustrious history as a research facility, being the site of a lot of breakthroughs in radio astronomy. However, NSF funds several other newer radio astronomy facilities. Is Arecibo still a world-class facility or is it outclassed by sites like the Very Large Array in New Mexico? Does Arecibo have unique capabilities that are not found elsewhere?*

The NSF Division of Astronomical Sciences (AST) responds to community recommendations as reflected in National Academies decadal surveys. In those surveys, the last recommendation for a single-dish, centimeter-wavelength radio telescope was made in the 1970 decadal survey, nearly 50 years ago. These single-dish telescopes generally have been supplanted in community priorities by large arrays of smaller radio telescopes that can work together as interferometers at either centimeter or millimeter wavelengths. These interferometers are much more versatile than large single-dish centimeter-wavelength telescopes and are able to produce higher-resolution images. Examples of such community recommendations for radio interferometers as major facility projects include the Very Large Array (VLA: initial decadal survey recommendation in 1970, Expanded VLA recommended in 1990 and 2000); the Very Long Baseline Array (1980 decadal survey recommendation); and the Atacama Large Millimeter/submillimeter Array (recommended as the Millimeter Array in the 1990 decadal survey, confirmed as ALMA in the 2000 decadal survey). Single-dish telescopes such as Arecibo cannot achieve the angular resolution to provide images of comparable quality and resolution to ground-based or space-based optical telescopes, or to the aforementioned radio interferometers. That high resolution is essential to studies of nearby and distant galaxies, exploration of regions of planet and star formation, and the imaging of exoplanetary disks forming around young stars.

Arecibo has a very large collecting area for observations at centimeter wavelengths, which provides enhanced sensitivity. The VLA, when operated with all its smaller dishes combined as a single instrument, has sensitivity that is about a factor of 5-6 poorer than Arecibo at a wavelength of 20 centimeters, improving to be only a factor of about 1.8 poorer at a wavelength of 4 centimeters. This high sensitivity, without very high angular resolution, is important for studies of point sources such as rotating neutron stars (pulsars) or for use in combination with other worldwide telescopes in long-baseline interferometry. At shorter centimeter wavelengths, the VLA continues to operate at high sensitivity, but Arecibo has no capabilities.

Arecibo also has a powerful radar transmitter for studying bodies in our solar system, a capability that does not exist on the VLA or other radio interferometers.

5. *Kitt Peak Observatory, the location of the Northern Hemisphere operations of NOAO, is in the process of divesting its facilities. NOAO is transferring operations*

of one of its telescopes to the Department of Energy and another to a university consortium. What are the reasons behind this change in Kitt Peak's operations?

The NSF Division of Astronomical Sciences (AST) continues to balance the science-enabling capabilities of its large facilities with the science-enabling mid-scale and individual investigator grants to community researchers. In 2011-2012, AST conducted a community-based Portfolio Review of its programs, as recommended by the 2010 National Academies decadal survey. This Portfolio Review recommended divestment of these telescopes on Kitt Peak because of their lower priority, relative to other facilities and the various research grants programs, in the delivery of the science recommended by the decadal survey. The operational changes in telescopes on Kitt Peak are enabling them to be available for various community science projects, so that these telescopes are still available for astronomical discovery, but with reduced requirements for ongoing NSF funding.

6. *LSST will produce the largest publicly available data set in history. As such, the project must spend a lot of its resources on creating its data infrastructure in addition to building a massive telescope array. What factors led to LSST making the decision to make the data set publicly available and what are some benefits that the project managers see from potentially doing so?*
 - a. *What fraction of LSST's maintenance costs will go towards maintaining the data and supporting the online infrastructure?*

The LSST project is primarily funded by the U.S. Federal Government through NSF, the lead partner and majority funder, and the Department of Energy (DOE). Construction costs are capped at \$473M for NSF and \$168M for DOE, with significant additional DOE funding for their share of the cost of commissioning. (Commissioning is included in the basic NSF construction budget, but is allocated separately by DOE.) In addition, the agencies are committed to the ten-year prime mission, and over that period we estimate further NSF investment of more than \$300M (over \$150M for DOE) for the operations and maintenance costs and the support of scientific investigations.

At that level of taxpayer investment, it is important that all collected data should be freely available to the US community, including professional and amateur scientists, educators, and the interested public. This is part of the U.S. government commitment for open access to data and the results from federally funded research. It also is consistent with the 2014 recommendations from the Astronomy and Astrophysics Advisory Committee as embodied in their document on "Principles for Access to Large Federally Funded Astrophysics Projects and Facilities", available at <http://www.nsf.gov/mps/ast/aaac.jsp>.

a. What fraction of LSST's maintenance costs will go towards maintaining the data and supporting the online infrastructure? Before the NSF agreed to support construction, we required a detailed estimate of the future operations and maintenance (O&M) costs. At that time, more than half of the anticipated O&M budget was devoted

to data collection and dissemination. Now that construction is well under way, the Project team is re-planning operations and revisiting those estimates. Although that plan is still in progress, initial results agree that the online infrastructure will take over 50% of the O&M budget, perhaps exceeding 60% if the dedicated educational data services are included. NSF expects to receive a detailed operations proposal for LSST in 2017, with a full external merit review to be carried out prior to the onset of significant operations funding in Fiscal Year 2019.

7. *The Daniel K. Inouye Solar Telescope (DKIST) project was first approved by the National Science Board (NSB) in 2009 for \$298 million. In August 2013, the project cost was re-baselined to \$344 million and the award expiration date was extended from December 2017 to July 2019. The NSF Inspector General subsequently issued an Alert Memo warning of further cost and schedule risk for the project. What steps has NSF taken to address those concerns, and how confident are you that you will meet the new project deadline and on budget?*

NSF has taken numerous steps to strengthen oversight of Large Facilities projects over the past two years. DKIST is now approximately 70% complete and NSF has high confidence that the project will be completed within budget and schedule requirements. The following are the actions taken by NSF that are specific to DKIST:

Over the past year, NSF's Division of Astronomical Sciences (AST) and Large Facilities Office (LFO) have conducted three targeted reviews (Annual Project Status, Business Systems Review, and Contingency Assessment) using a combination of external panelists, expert consultants, and experienced NSF staff. AST and LFO will initiate two additional reviews in the fall of 2016: (1) an independent risk evaluation to further assess the adequacy of DKIST's management of remaining risks, and (2) a validation of the project's Earned Value Management System (EVMS).

NSF has developed new internal operating guidance that codifies NSF's procedures for obligating, allocating, and tracking budget contingency on all Large Facilities projects. This guidance will be implemented on all future obligations to the DKIST project and, in combination with the completed Contingency Assessment, will strengthen NSF's oversight of contingency use. This new guidance codifies implementation of Recommendation 4.1 of the National Academy of Public Administration (NAPA) report entitled "National Science Foundation: Use of Cooperative Agreements to Support Large Scale Investments in Research", in which NSF was advised to retain control over a portion of the budget contingency to improve its oversight.

As stated above, the LFO assisted AST by conducting a detailed assessment of the DKIST budget and schedule contingency. The assessment found that management of contingency is in compliance with current NSF guidelines and requirements. The remaining project budget and schedule contingency appear to be adequate based on accepted industry standards at an 80% confidence level for an on-budget and on-time completion.

8. *The last decadal survey recommended a Mid-Scale Innovations Program at NSF, which you and other witnesses have discussed. Has that been successful? What are the barriers to implanting it as recommended in the decadal?*

The Mid-Scale Innovations Program (MSIP) is a program of the NSF Division of Astronomical Sciences (AST), initiated in response to the decadal survey. AST has now carried out two rounds of MSIP proposal and selection. MSIP has proven very successful in receiving and funding proposals for experiments at the low end of the funding range recommended by the decadal survey. However, the decadal survey recommended that MSIP be funded at the level of about \$40 million annually, while NSF has achieved levels of only \$19.25 million in Fiscal Year 2016 (\$18.00 million requested in Fiscal Year 2017). The primary reason for the lower funding level is that the AST budget in FY 2016 is at the same level as in FY 2010, while the annual funding required to operate AST national facilities has increased by approximately \$23 million over the same period. This overall facility funding increase, in spite of reductions at Arecibo Observatory, the National Optical Astronomy Observatory, and the National Solar Observatory, has been caused primarily by the ramp up to full operations of the Atacama Large Millimeter/submillimeter Array and the beginning of the operations funding ramp for the Daniel K. Inouye Solar Telescope. The full operations funding of these important facilities is part of the commitment that NSF made when it began their construction.

MSIP was the subject of two findings by the National Academies Midterm Assessment⁷ of Agencies' progress in responding to the 2010 decadal survey; those findings are quoted below:

Finding 3-3: Implementation of the NWNH [New Worlds, New Horizons decadal survey] recommendation of MSIP has been possible only by subsuming previous programs into MSIP and by aggressive divestment from older facilities. The total NSF-AST funding for mid-scale initiatives has dropped by nearly a factor of two since the start of the decade, in stark contrast to the NWNH recommendation of MSIP as a new initiative which would expand opportunities for mid-scale projects.

Finding 3-4: Despite limited resources for MSIP, NSF-AST has funded an exciting set of highly ranked proposals in a heavily oversubscribed competition. Some mid-scale programs recommended by NWNH have also moved forward with funding from DOE and from the NSF Physics and Polar Programs. The scientific promise of these projects confirms the NWNH expectation that a mid-scale program would enable major advances that respond nimbly to opportunities on a diverse range of science topics.

9. *Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) achieved its core goal almost immediately after becoming operational – it*

⁷ <https://www.nap.edu/catalog/23560/new-worlds-new-horizons-a-midterm-assessment>

detected gravitational waves in September of 2015. With the amount of investment in the facility, it is imperative that LIGO continues to be the site of groundbreaking research. What will LIGO's operations focus on moving forward?

The immediate near-term focus of LIGO operations will be to reach design sensitivity. The facility is still a factor of three away from reaching this goal, as expected, although reaching the goal is still within design expectations. Reaching design sensitivity should increase the probability of detecting weaker signals. In particular, this will enhance the likelihood of detecting mergers of two neutron stars, in addition to making LIGO more sensitive to the black-hole mergers that have been reported to date.

10. Laser Interferometer Gravitational-Wave Observatory (LIGO) was able to detect gravitational waves after receiving a major upgrade that became operational in 2015. Are there any further additions to LIGO's facilities that will increase its ability to detect gravitational waves of lower magnitude in the next few years?

LIGO is considering a number of options that could be implemented that would offer an enhancement of current capability within the present design. Some of these have been discussed at a recent workshop held by the LIGO scientific collaboration. The present focus remains on exploitation of the current detection capability, as noted in the response to the previous question.

Questions submitted by Rep. Dana Rohrabacher

1. *Can you describe the environmental impact process that is currently being conducted on Arecibo? And based on those findings, when might a decision be made on if the facility's operations are to be reduced or shut down by NSF, and what would the timeline be for NSF to implement that decision?*

The process currently being carried out by NSF is responsive to three primary statutes: the National Environmental Policy Act (NEPA), the National Historic Preservation Act (NHPA), and the Endangered Species Act (ESA). The Environmental Impact Statement (EIS) process is established under NEPA, and is being carried out concurrently with compliance with Section 106 of NHPA and Section 7 of ESA.

For NEPA, the EIS process includes public scoping meetings to discuss preliminary proposed alternatives and any considerations regarding the scope of the environmental analysis that the public wishes to bring to NSF's attention. The scoping process for the Arecibo EIS will be followed by publication of a Draft EIS in the autumn of 2016, again accompanied by public hearings and comments. NSF then will prepare a Final EIS, with a target publication date in the spring of 2017. In July 2016, NASA indicated its wish to be a cooperating agency in preparation of the EIS, so NASA will be fully engaged in the EIS activities.

Concurrently, the NHPA process involves consultation with the State Historic Preservation Officer (SHPO) and the public, identification of historic properties, assessment of possible adverse effects, and (if necessary) resolution of adverse effects. Consultation with the SHPO and the Advisory Council for Historic Preservation has already begun and will continue throughout the process.

The ESA prohibits actions likely to jeopardize the existence of listed species. As required under Section 7 of the ESA, NSF has begun consultation with the U.S. Fish and Wildlife Service regarding any listed species that could be affected by any of the possible alternatives for operational changes at Arecibo Observatory.

The outcome of all the processes above, plus additional programmatic (e.g., budgetary, risk, and scientific considerations) will result in a Record of Decision to be issued by NSF. That Record of Decision will include a selected alternative and will be accompanied by any mitigation measures deemed necessary to carry out the alternative. NSF currently is targeting the summer of 2017 for this Record of Decision. NSF is committed to an open process and full consideration of any issues that are identified during the actions described above, so the target date could slip if additional work is required to address new issues that arise. Following issuance of the Record of Decision, NSF will proceed to carry out its implementation on a timeline

that is consistent with the choices made in the Record of Decision, the availability of funds, and any other programmatic or legal considerations that must be put in place before implementation.

2. *In May 2016, Dr. James Green, Planetary Science Division Director, NASA, wrote a letter to NSF describing the ongoing importance of the Arecibo Planetary Radar, particularly for observing Near-Earth Objects (NEOs). The letter states that the Arecibo Planetary Radar "has the highest sensitivity in the world for NEO observations, and therefore is a particularly important asset for NASA's NEO tracking and characterization efforts, which are mandated by law." In your testimony, you claimed that new NSF telescopes coming online in 2019 and 2022 would be able to have similar capabilities. Can you describe Arecibo's contributions to fulfilling near earth object tracking and characterization, and explain how and when LSST or DKIST may be able to fulfil that important mission?*

NSF certainly did not intend to characterize the Daniel K. Inouye Solar Telescope (DKIST) as playing any role in Near-Earth Object detection or characterization. As an observatory that will provide fundamental understanding of the Sun, DKIST is a very high priority facility for understanding the origins of space weather, a potential threat to our technological society on Earth.

The Large Synoptic Survey Telescope (LSST), which will begin its 10-year survey in 2022, will be a very wide-field optical telescope used to detect many thousands of Near-Earth Objects (NEOs), measure their orbits, and provide some characterization of their properties. NASA presently has a mandate from Congress to find, track, and catalogue 90% of NEOs larger than 140 meters (460 feet) in diameter by 2020, but the census is incomplete for NEOs in the diameter range from 140 meters to a few hundred meters in diameter. According to the NASA Planetary Defense Office web site (<https://www.nasa.gov/planetarydefense/overview>), accessed on August 25, 2016, there are approximately 25,000 NEOs more than 140 meters in size, with 6,800 currently known, and about 500 being discovered per year. At that rate, the survey of NEOs greater than 140 meters in size would be approximately 40% complete in 2022; depending on the exact models of NEOs and simulations of surveys, LSST should be able to bring that completeness number to approximately 80%. Thus LSST will be a critical contribution by NSF and the Department of Energy to the fulfillment of NASA's mission.

In contrast to optical and infrared telescopes, the Arecibo and Goldstone radars can only study known asteroids, but cannot discover or survey previously unknown asteroids. Thus the "missing" NEOs referred to above can never be discovered by Arecibo or Goldstone. Optical and infrared survey telescopes must discover the NEOs and track them for periods of weeks or months to determine orbits accurately enough for targeting by radars. Once the optical telescopes can determine a NEO

orbit well enough for radar observations to be possible, and if the NEO is within the range of accessibility for the radar (smaller angular region of accessibility, but greater distance, for Arecibo when compared to Goldstone), the radar then can be used to determine a much more precise orbit. In particular, radar telescopes are sensitive to the range, or distance to an object as well as its position in the sky, while optical telescopes find distance much less precisely by tracking the motion of a NEO over time. In addition, the radar observation can “image” the object to determine critical characteristics, such as whether the asteroid is a single body or multiple objects. Optical telescopes such as LSST, or other optical and infrared telescopes, can determine approximate properties of a NEO (e.g., size and composition) by measurement of its brightness at different wavelengths, but this characterization is much less precise than for radars.

Thus, LSST will play a major role in the discovery and tracking of asteroids, but can provide only rough characterization and a less precise orbit than the planetary radars on Goldstone and Arecibo.

3. *In 2015, NSF published a “Dear Colleague Letter” asking for proposals on how to plan Arecibo’s continued operation. Proposals are expected to include a reduced funding commitment from NSF and possibly a transfer of Arecibo’s operations to another agency. Proposals were supposed to be submitted by January 15, 2016. What have some of the ideas been for how to continue Arecibo’s viability as a research facility? Do any of them include it remaining an NSF facility in the long run?*

In October 2015, NSF issued a Dear Colleague Letter (DCL) requesting community responses on viable concepts for the future continued operation of the Arecibo Observatory. Responders were asked to specifically consider strategies and goals for continued operations that involve a substantially reduced funding commitment from NSF and were advised that responses could also include concepts involving the assumption of title and ownership of the Arecibo Observatory by the responder.

By the January 15, 2016 submission deadline NSF received six responses from the community; another interested party submitted a response subsequent to the deadline. In general, the DCL responses included a mix of concepts, some of which included NSF retaining title of the facility, including a significant long-term funding commitment, and others which involved transfer of title with a concomitant reduction of NSF funding. As the details of the responses are proprietary to the responding organizations, NSF cannot provide specific details, but all submitted DCL responses include plans for continuing some or all of the current science operations.

4. *Dr. Ulvestad, what work on NEO observations has been performed, including their purpose, over the past 3 years at Arecibo Observatory? Would that work have been better performed elsewhere?*

Arecibo Observatory has successfully observed a total of 95, 79, and 69 Near Earth Objects (NEOs) during the past three calendar years (2015, 2014, 2013). The purpose of these observations has been to better characterize the physical and orbital properties of these objects. Through improved characterization, Arecibo makes a contribution to the ultimate determination of whether or not a specific asteroid is potentially hazardous, or perhaps even a potential target for human space flight accessibility.

The powerful Arecibo radar transmitter combined with the telescope's large collecting area enable Arecibo Observatory to detect nearly any asteroid larger than approximately 10 meters within 6 lunar distances of the Earth, as long as that asteroid is within the portion of the sky that can be observed by the Observatory (within 20 degrees of the zenith). In 2015, more than 1500 NEOs were discovered by optical and infrared telescopes. The fact that Arecibo Observatory observed only a small fraction of the newly discovered NEOs is a combination of several factors, including: some NEO discoveries are made in portions of the sky inaccessible to the Arecibo radar, discoveries are made and announced after specific NEOs are outside the window of opportunity (either in angular location or in distance) for observation with the Arecibo radar, or the telescope is previously scheduled for other scientific activities (planetary radar science is one of three Arecibo scientific priorities).

5. *Dr. Ulvestad, you stated that NEO "tracking can also be done with optical and infrared telescopes." Can you provide greater clarity about how the capabilities of the Arecibo Observatory compare with our best ground-based optical and infrared telescopes with regard to important NEO tracking and characterization parameters:*
 - a. *Sensitivity?*
 - b. *Maximum resolution for imaging?*
 - c. *Maximum distance for observation?*
 - d. *Percentage of time available for astronomy observations?*
 - e. *Availability for short-notice, target-of-opportunity observing requests?*

Optical and infrared telescopes have much different characteristics than radar telescopes, so quantitative comparisons of some properties are not possible. We attempt to provide a mix of qualitative and quantitative responses below:

- a. **Sensitivity?** NEOs shine primarily by reflected sunlight. Thus they are visible at optical and infrared wavelengths, but are essentially invisible at radio wavelengths unless illuminated by a radar. For a 140-meter-diameter NEO that is one Astronomical Unit (1 AU), or approximately 93 million miles (150 million kilometers) from the Earth, and 1 AU from the Sun, the NEO will be easily detectable within a few seconds by the Large Synoptic Survey Telescope (LSST). The main reflector of LSST will have an effective diameter of 6.7 meters; depending on the exact asteroid properties, an optical or infrared telescope in the diameter range of 2-4 meters could detect the 140-meter NEO at 1 AU in an observation of a few seconds to a few minutes. For Arecibo to

target the same NEO for radar return with a signal-to-noise ratio of 30 (given reasonable assumptions about the NEO shape and rotation speed), the NEO would need to be about 10 times closer, within 0.1 AU of the Earth.

- b. **Maximum resolution for imaging?** A NEO of 140 meters in diameter would have to be inside the orbit of the moon to cover more than a single pixel in an image from an optical telescope. so imaging the details of such an object with a ground-based optical telescope generally is not possible. Imaging resolution of a few meters is achievable using the Arecibo radar, once an object is within the detectable range, and depending on the signal-to-noise ratio. (For the hypothetical 140-meter NEO at the distance of about 0.1 AU, the imaging resolution is likely to be poorer than a few meters because of the limited signal level.)
- c. **Maximum distance for observation?** As noted in the sensitivity section above, the maximum distance depends on asteroid size, reflectivity, and other factors. For a 140-meter NEO, the limit for Arecibo radar usage is roughly 0.1 AU. For the same NEO, the detection limit for LSST in a few seconds typically is well over 1 AU unless the NEO is behind the Sun. Since NEOs shine by reflected sunlight, the exact distance limit depends sensitively on the distance from the Sun and the viewing angle between Sun and NEO.
- d. **Percentage of time available for astronomy observations?** Most NSF telescopes in optical, infrared, and radio wavelengths have the majority of their time available for astronomy observations, with regularly scheduled downtime for maintenance activities. Some are operated in partnerships that provide guaranteed time to particular groups, usually to do astronomy. Arecibo has the majority of its time available for astronomy observations. However, the cost of diesel fuel for the generators and limitations on emissions from the generators restrict the amount of time that is actually spent using the planetary radar. Some of the radar time is spent on other scientific goals in addition to observing NEOs.
- e. **Availability for short-notice, target-of-opportunity observing requests?** This is highly observatory-dependent, and depends on the mission and observing method of a particular telescope. Most NSF telescopes like the Gemini Observatory and the Very Large Array operate predominantly with queue-based scheduling that can be changed easily, so they are highly available for approved short-notice observing requests. Arecibo operates more in the older “classical” mode of observing, where the telescope has a fixed observing schedule that is somewhat more difficult to re-arrange. In general, NSF telescopes are not staffed sufficiently to constantly re-organize their time allocation; although short-notice requests can be accommodated when needed, accommodating too many such requests would reduce the overall science return from the telescope. Hence, short-notice requests must be evaluated to have a high priority in order to interrupt the optimized smooth operations of the observatory.

Questions submitted by Rep. Donna Edwards, Ranking Member, Subcommittee on Space

1. *The Kepler mission has identified a population of extra-solar planets that future missions, such as the James Webb Space Telescope and the Transiting Exoplanet Survey Satellite, can explore in more detail. Do we have the technologies-the telescopes and the instruments to do the spectral analysis to search for biosignatures in the atmospheres of habitable exoplanets?*
 - a. *If not, is NSF currently investing in technologies that will enable this research?*
 - b. *When do you expect this capability to be available to scientists?*

One of the ultimate goals in the search for exoplanets is to find life outside of our solar system. This search is conducted by first hunting for planets with telescopes like NASA's Kepler Space Telescope and NASA's planned Transiting Exoplanet Survey Satellite (TESS), which look for dips in the brightness of a star as a planet passes in front of it, or with the many ground-based observatories measuring the slight changes in a star's motion caused by the gravitational tug of an orbiting planet (the Doppler or radial-velocity method).

Having found an exoplanet, the next step is to determine whether the planet is habitable, based on characteristics such as the planet's size, mass, and distance from the star it is orbiting. For a planet to be considered "habitable," it must be capable of maintaining liquid water on its surface. The presence of water in liquid form most likely is feasible only if the temperature is "reasonable" (i.e. within 0 to 100°C) and the planet is enveloped by an atmosphere of some kind.

The final (and most difficult) step is to take a spectrum of the planet. By observing peaks or dips in the spectrum caused by emission or absorption of light at specific wavelengths by molecules in the planet's atmosphere, researchers may determine if the atmosphere contains any "bio-signatures". Two methods are currently available: (1) direct spectroscopic-imaging of the planet's intrinsic light or light as reflected from the parent star; or (2) transmission spectroscopy, where starlight is observed through the planet's atmosphere as the planet passes in front of the star.

When the planet is offset from the star (when viewed in projection on the sky), the planet's spectrum may be measured if the starlight is suppressed in some way – usually an opaque "mask" is used to block the light from the star. A number of new instruments on 8-10 meter sized ground-based telescopes (e.g. the Gemini Planet Imager) have been developed for such observations. The main challenge with this technique is the precise suppression of the starlight and the removal of scattered light: Earth-sized planets are 1-10 billion times fainter than their parent stars. Even with the most stable systems currently available, the usefulness of this technique is limited to massive gas-giant planets that orbit their host star well beyond the habitable zone. The next generation of instruments on thirty-meter class telescopes, when combined with improved adaptive optics techniques, may improve the situation in the next decade, although the suppression of the star by a factor of a billion remains an unsolved challenge.

Space-based systems developed by NASA are likely to fare better when trying to directly image exoplanets, since they do not have to contend with the telescope pointing, image quality, and thermal stability issues faced by ground-based telescopes observing through our Earth's turbulent atmosphere. But due to the relatively small size of its mirror, even the coronagraph instrument on NASA's planned Wide Field Infrared Space Telescope (WFIRST) will be a factor of 10-100 short of the light suppression and angular resolution needed to study the spectra of Earth-sized planets within the habitable zones of nearby stars. There also have been suggestions for an external "starshade" to enable NASA's James Webb Space Telescope (JWST) to carry out similar observations, but this is not feasible because JWST will not have the necessary transponders or pointing capability required to line up with the starshade.

The challenge with the second method, the transmission spectroscopy technique, is distinguishing the very weak features in the spectrum from the bright, noisy light from the background star. Probing the atmospheres of Earth-like planets will only be possible with the very largest telescopes, and may again be best done from space where the spectrum isn't "contaminated" by passage of the light through the Earth's atmosphere.

- a. **If not, is the NSF currently investing in technologies that will enable this research?** NSF invests in the development of instrumentation concepts that support these goals. This instrumentation is under development for ground-based telescopes, probably ultimately as precursors for the thirty-meter telescopes planned in the next 10 years. Technology developed under grants from both the NSF and NASA is being used for ground-based and space-based telescopes. NASA invests directly in the technologies for the space-based telescopes such as JWST and WFIRST.
 - b. **When do you expect this capability to be available to scientists?** As mentioned above, NASA's WFIRST mission would have an improved method of blocking starlight, but still is not expected to have suppression sufficient to take spectra of Earth-sized planets in the habitable zones. The thirty-meter class telescopes will use this instrumentation and techniques as well, and can support improvements in instrument development in the coming years. However, as noted above, suppression of the light from the host star by more than a factor of a billion is an unsolved problem, and we cannot predict when it might be possible from the ground-based observatories that are within NSF's purview.
2. *What needs to be done to improve the decadal survey process for estimating the development cost of large-scale facilities and missions?*

The National Academies recently carried out a NASA-funded assessment of the processes of the last decadal surveys. Various recommendations were made regarding the cost estimation for NASA missions. However, the process of estimation was very different for space-based missions and ground-based facilities, so we will leave to NASA any comments on the utility of the process for their space-based missions. With respect to ground-based facilities, the passage of six years has shown that the decadal survey's assessment of the construction costs provided by advocates of large future

ground-based facilities was at least qualitatively correct. Hence this assessment was a useful contribution to the decadal survey and to NSF in making decisions about construction readiness and risks. From NSF's point of view, perhaps the biggest improvement would be a provision of more detailed information about the assessment of the individual facilities. This would have to be balanced against the need of the facility advocates to keep some of their material proprietary.

3. *What is Arecibo's role in defending the Earth against potentially hazardous near-Earth objects? What is the National Science Foundation doing to ensure the continuity of this capability?*

Defense of the Earth against potentially hazardous near-Earth objects is the mission of NASA and its Planetary Defense Office. This role was specified in a 2010 letter from the Office of Science and Technology Policy (OSTP), responding to NASA Authorization language requiring that OSTP outline agency responsibilities for protecting the Earth from potentially hazardous objects.⁸ An end-to-end description of this mission may be found at <https://www.nasa.gov/planetarydefense/overview> and will be summarized only briefly here.

A large chain of activities is needed in the execution of the planetary defense mission. First, potentially hazardous Near-Earth Objects, or NEOs, must be identified by means of surveys with infrared and optical telescopes. Following identification, NEOs must be tracked with such telescopes for a sufficient period of time to determine their approximate orbits. NSF's largest contribution to this mission will be the construction of the Large Synoptic Survey Telescope (LSST) and the execution of its survey program beginning in 2022; it is estimated that LSST will increase the identification fraction of NEOs larger than 140 meters in diameter from about 40% in 2022 to roughly 80%. Detailed studies are under way to better constrain this number.

Following identification and orbit determination for an NEO, its orbit and structure may be found with greater precision using radar observations from either Arecibo or Goldstone. The contribution of Arecibo depends on whether the NEO passes near enough to Earth and within the angular window accessible from Arecibo. The more precise orbit will provide a better determination about whether the NEO might threaten Earth some day, and the determination of the structure will give further information about how much damage it might cause.

The last step in planetary protection would be deflection or re-direction of a threatening NEO. This step requires mission capabilities that have not yet been developed. Some description of the process of deflection and the process of warning

⁸ <https://www.whitehouse.gov/sites/default/files/microsites/ostp/ostp-letter-neos-house.pdf>

and response (involving the Federal Emergency Management Agency) may be found at the NASA web site referenced above, and is beyond the scope of NSF's mission.

NSF continues to make Arecibo available for planetary radar observations of NEOs, has informed NASA on several occasions of the reduced need for Arecibo in the execution of NSF's science mission, and has also engaged NASA in discussions of NSF's decision process for Arecibo. In late July, NASA indicated its wish to be a cooperating agency in NSF's Environmental Impact Statement process for Arecibo. NSF continues to seek collaborations with interested parties for Arecibo that would allow Arecibo to remain available to NASA for the execution of its mission.

Responses by Dr. Angela Olinto

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 ANGELA V. OLINTO, *Chair*

September 7, 2016

The Honorable Brian Babin, Chairman
 Subcommittee on Space
 United States House of Representatives
 Washington, DC 20515

The Honorable Barbara Comstock, Chairwoman
 Subcommittee on Research and Technology
 United States House of Representatives
 Washington, DC 20515

The Honorable Donna Edwards, Ranking Member
 Subcommittee on Space
 United States House of Representatives
 Washington, DC 20515

The Honorable Dan Lipinski, Ranking Member
 Subcommittee on Research and Technology
 United States House of Representatives
 Washington, DC 20515

Dear Chairman Babin, Chairwoman Comstock, Ranking Member Edwards, and Ranking Member Lipinski:

Thank you for your interest in Astronomy, Astrophysics. I am pleased to enclose below answers to the questions I received from Chairman Babin and Ranking Member Edwards sent on August 24, 2016 as a follow up to the July 12, 2016, hearing titled "*Astronomy, Astrophysics, and Astrobiology*" of the Committee on Science, Space, and Technology.

Questions submitted by Rep. Brian Babin, Chairman, Subcommittee on Space

1. Arecibo Observatory obviously has a very illustrious history as a research facility, being the site of a lot of breakthroughs in radio astronomy. However, NSF funds several other newer radio astronomy facilities. Does Arecibo still have unique capabilities with a role to play in making discoveries? What is its value to the research community?

The *New Worlds, New Horizons (NWNH) Decadal Survey* recommended that NSF investments be focused on achieving transformative science through a new generation of state-of-the-art facilities. In NWNH, the best scientific breakthroughs in the radio range of the electromagnetic were predicted to come from the Atacama Large Millimeter/submillimeter Array (ALMA). To complement ALMA a new millimeter survey telescope, named CCAT (for Cerro Chajnantor Atacama Telescope), was prioritized in the medium scale ground category.

As stated in the recent (August 2016) National Academies report "*New Worlds, New Horizons: A Midterm Assessment*" (hereafter, *Midterm Assessment*), on page 2-6: "*The completion and successful operation of ALMA are a remarkable success and the culmination of significant*

investment by NSF through the MREFC program." However, there has been no new funding at NSF to enable CCAT to proceed past an initial design (see discussion in *Midterm Assessment* Chapter 3).

Given the budgetary realities of the decade compared to NWNH planning, the *Portfolio Review* recommended that NSF-AST consider divestment of Arecibo later in this decade. This recommendation took into consideration international obligations and the remaining scientific benefits of Arecibo.

2. In their annual report, the Astronomy and Astrophysics Advisory Committee (AAAC) placed an emphasis on the development of Stage 4 Ground Based Cosmic Microwave Background (CMB) Experiments. What scientific achievements do you hope to gain from increasing the focus of NSF on Cosmic Microwave Background research?

NSF and the Department of Energy (DOE) are working on a plan for a fourth generation ground-based CMB (Stage 4 or S-4) experiment together with the scientific CMB community. Third generation experiments are now reaching the sensitivity to start probing the earliest moments of the universe. Fourth generation experiments are intended to be orders of magnitude more capable than current experiments at measuring CMB temperature and polarization fluctuations. This unparalleled effort will enable the possible discovery of primordial gravitational waves from the early universe, testing cosmic inflation models. It will also provide precise measurements of the properties of neutrinos and the dark energy.

The AAAC noted the importance of maintaining US leadership in CMB science. The planning for CMB Stage 4 should maximize the potential for new scientific discovery through a well-coordinated inter-agency strategy.

3. The Astronomy and Astrophysics Advisory Committee (AAAC) pointed to a particular challenge when implementing the Portfolio Review Committee (PRC) report recommendations. That challenge was adhering to the requirement to maintain operations at existing observatories while constructing new facilities. Can you elaborate on those challenges and offer any insight to how they could be mitigated?

The strategy underlying the NSF *Portfolio Review* is that in order to achieve the goals of the *NWNH Decadal Survey* given the budgetary constraints, it would be necessary to transition current resources from existing facilities to a new generation of facilities that can achieve transformative breakthroughs. As stated in the *Midterm Assessment*, "*Painful though they are, the divestments recommended by the Portfolio Review are essential to maintaining other key aspects of the NSF-AST program. However, the division's new facilities—ALMA, DKIST, and (at the end of the decade) LSST—are more sophisticated and more complex than the facilities being divested, and they are correspondingly more expensive to operate. Divestment alone will not resolve the budget stresses imposed by rising facilities costs.*"

The AAAC has reviewed the NSF implementation of the *Portfolio Review* and its efforts to comply with Congressional guidelines to provide timely reporting of all divestment actions. The additional requirement to request sufficient funding to maintain operations at both new and existing observatories as additional facilities come online in future years, however, is difficult to accommodate in the present budget envisioned by the NSF.

The most important mitigation strategy would be to ensure that discontinuities in observing capabilities be minimized by the most efficient and rapid transitions possible. The AAAC recommends that "*Strong efforts by NSF for facility divestment should continue as fast as is practical. Efforts to explore partnerships, interagency cooperation and private resources to maintain some access to facilities for the US community that may mitigate the loss of open access should continue.*"

Transferring the cost of operating a facility outside of the NSF/AST budget is preferable to complete loss of a capability from the suite of capabilities used by US researchers."

4. What are the most important technological advancements that are needed to further astrophysics research? What advancements should be our highest priority?

NWNH identified the need to continue support for innovative technologies for future telescopes. It recommended that NASA start an *Intermediate Technology Development* program targeted at technology readiness level (TRL) range between 3 and 5 (NWNH page 21). NASA established a *Strategic Astrophysics Technology* in response to that recommendation. In addition, NWNH identified a few areas as ripe for technological advancements in this decade. The space-based medium-scale priorities were the "*New Worlds Technology Development Program*" to advance starlight suppression technology (such as coronagraphy and starshades) preparing for a mission to Image Habitable Rocky Planets in the 2020 decade. The second priority in this category was the "*Inflation Probe Technology Development Program*" to develop technologies to enable CMB studies of cosmic inflation. In addition technology development for observations of gravitational waves from space and a future X-ray mission align well with the priorities of large-class space missions in NWNH, which prioritized these two space observatories after WFIRST and the Augmentation of the Explorers program.

The following findings from the Midterm Assessment address the current stage of these technologies and preparations for the next decadal survey.

On page 4-8, "*FINDING 4-5: Coronagraph technology has matured rapidly over the past 2 years, addressing one of the key recommendations of the 2014 report Evaluation of the Implementation of WFIRST/AFTA in the Context of New Worlds, New Horizons in Astronomy and Astrophysics.*"

On page 4-10, "*RECOMMENDATION 4-2: In the remainder of the decade, NASA should treat support of Euclid participation beyond the existing commitments to the European Space Agency as lower priority than support of the Explorer program, gravity wave technology development, and X-ray technology development.*"

The Midterm Assessment reiterates on page 4-18, from "*Evaluation of the Implementation of WFIRST/AFTA: Finding 1-7: The WFIRST/AFTA coronagraph satisfies some aspects of the broader exoplanet technology development program recommended by NWNH by developing and demonstrating advanced coronagraphic starlight suppression techniques in space.*"

Further on the same page, "*FINDING 4-11: The current planned decadal investment in NWNH-recommended technology development and precursor science exceeds the level envisioned in NWNH.*"

The committee believes that NASA's continued development of coronagraph and starshade technology at a modest level for mission design, scope, and capability is a positive step and that this activity would be profitably evaluated by the next decadal survey. However, given the substantial advances already enabled by WFIRST coronagraph development, the committee assigns higher priority to supporting adequate gravitational wave technology development than to further exoplanet technology development beyond WFIRST."

Finally on page 4-19, "*FINDING 4-12: The Inflation Probe Technology Development program is well aligned with the recommendations of NWNH, with NASA, NSF, and DOE supporting technology development and precursor science. Third-generation ground-based efforts and a suborbital program are taking place, targeting CMB B-mode polarization. The proposed CMB-S4 program would push the limits of what can be achieved from the ground and advance understanding of the technology and science requirements for a possible future space mission.*"

5. What are the major differences between government-funded and private sector astrophysics and astronomy research? Does private sector research carry the same weight in the scientific community?

Historically US leadership in optical and infrared astronomy has been supported by highly successful private-public partnerships. Large optical and infrared telescopes have been traditionally constructed with private and other non-federal funds (e.g., state and international) and supported for operations and innovative instrumentation through competed public funding. Over the last decade, it has become increasingly difficult to sustain this model.

Quoting again from the Midterm Assessment report: *“The public/private partnership in astronomy the United States has in the past hundred years been a strength of U.S. astronomy. However, given the recent difficulties encountered by the Thirty Meter Telescope and Giant Magellan Telescope projects, the cancelling of the Telescope Systems Instrumentation Program, lack of a plan for NSF participation in future optical 30-meter telescope planning and construction, and the disconnect between the public decadal process and private deliberations and funding, it may be time to consider developing a process for a unified effort between the public and private spheres in an attempt to optimize the U.S. astronomical enterprise as a whole. Therefore, the committee believes that engaging from the outset the private sector of U.S. astronomy, as well as private philanthropies, in the upcoming survey process could be helpful to the eventual outcome of the 2020 decadal process.”*

In addition, the AAAC has emphasized in a statement of *Principles of Access*, that the community will benefit most from a policy of providing the broadest scientific participation in private and foreign astronomy projects.

6. Please provide your perspectives on the Associations of University’s for Research in Astronomy (AURA) proposal for a High-Definition Space Telescope (HDST).

NASA has begun to study large mission concepts as input to the 2020 Decadal Survey. NASA has appointed Science and Technology Definition Teams (SDTs) and initiated four large mission concept studies: X-ray Surveyor, Far Infrared Surveyor, Habitable Exoplanet Imaging Mission, and Large Ultraviolet/Optical/Infrared Surveyor (LUVOIR). AURA’s concept paper addresses the LUVOIR mission concept and proposes achieving high-resolution spectral data on potentially habitable exoplanets. The 2020 Decadal Survey will review this and other large concepts.

7. In 2015, NSF published a “Dear Colleague Letter” asking for proposals on how to plan Arecibo’s continued operation. Proposals are expected to include a reduced funding commitment from NSF and possibly a transfer of Arecibo’s operations to another agency. Proposals were supposed to be submitted by January 15, 2016. What have some of the ideas been for how to continue Arecibo’s viability as a research facility? Do any of them include it remaining an NSF facility in the long run?

The AAAC did not have access to the responses to the “Dear Colleague Letter” on Arecibo. We understand that they contain proprietary ideas and hence are not public.

Questions submitted by Rep. Donna Edwards, Ranking Member, Subcommittee on Space

1. In your prepared statement you mention NASA’s new super-pressure balloon technology. What type of science does this new balloon capability enable?

a. How important are such sub-orbital capabilities to astrophysics and why?

As discussed in NWNH page 22, *“Suborbital Program. The balloon and sounding rocket programs provide fast access to space for substantive scientific investigations and flight-testing of new technology.*

The balloon program in particular is important for advancing detection of the cosmic microwave background and particle detection. These programs also provide a training ground for the principal investigators of tomorrow's major missions." NWNH recommended a growth in funding for the suborbital program during this decade.

On page 150, NWNH adds that *"NASA's suborbital (balloon and rocket) programs enable scientific experiments with equipment ranging from particle detectors to X-ray, gamma-ray, infrared, and microwave instruments. They support substantive scientific investigations in areas such as CMB and particle astrophysics, fulfill essential needs in technology development, and provide invaluable hands-on training. Notably, key positions in mission development across NASA are occupied by people who received their training through participation in suborbital missions."*

The recent success of the NASA super-pressure balloon flight of Spring 2016 demonstrates that longer duration and very stable altitude flights are now possible for testing of new technologies for future space missions and for a broad science portfolio including CMB, particle astrophysics, and interstellar medium science, among other astronomy and astrophysics frontier topics.

(In full disclosure, I am currently the NASA principle investigator of a super-pressure balloon-borne mission to study the highest energy cosmic particles that reach the Earth. EUSO-SPB, the Extreme Universe Space Observatory from a Super Pressure Balloon, is planned for launch from Wanaka, New Zealand, in the Spring of 2017.)

2. Is the United States in danger of losing world leadership in astronomy and astrophysics? If so, what, in your view, are the most important things to do to ensure continued U.S. leadership in astronomy and astrophysics?

As mentioned in my written remarks, *"With the sustaining support from Congress, the well coordinated efforts of the agencies, and the enduring tradition of the community to prioritize its aspirations through the decadal survey process, US astronomy and astrophysics will continue to lead the world in our quest to understand the universe, its laws, origins, and future, and our own origins and future."* However, the AAAC is concerned about the balance of the portfolio. At both NSF and NASA competed grants and mid-scale programs are being squeezed by flat or declining budgets. These programs produce the new generation of scientists and ideas. Success rates have declined from about 30% in 2004 to 20% in 2014, and this is affecting the morale of the community. As we plan for a future with continued US leadership, investment in the next generation of scientists and ideas is crucial.

The AAAC urges continued leadership on the part of the federal agencies, the White House, and Congress to maintain the US position by investing in the next generation of scientists and new state-of-the art telescopes and instruments. It is also important to forge collaborations with other nations to enable access by the US community to leading facilities abroad. As emphasized in the AAAC *Principles of Access*, the scientific community will benefit most from a policy of providing the broadest scientific participation in private and foreign astronomy projects

On behalf of the Astronomy and Astrophysics Advisory Committee,
Sincerely yours,



Angela Olinto
Homer J. Livingston Distinguished Service Professor
Chair, Astronomy and Astrophysics Advisory Committee, 2015-16

Responses by Dr. Shelly Wright

Shelley Wright, Assistant Professor, University of California San Diego
 Physics Department
 Center for Astrophysics & Space Sciences

Response to the questions submitted for the record by Members of the Committee on Science, Space, and Technology for the July 12, 2016 hearing titled "*Astronomy, Astrophysics, and Astrobiology*".

1. *How have the advances in the study of exoplanets and astrobiology affected your work and SETI's broader search for extrasolar signals?*

Astrobiology studies have shown that constituents and conditions we believe are necessary for life are common and perhaps ubiquitous in the Milky Way galaxy. A plethora of prebiotic molecules have now been detected in molecular clouds, including biologically important molecules like amino acids, sugars, and imines. Such detections suggest that reactants necessary for building large, complex organic structures may be formed readily in proto-planetary environments. In addition to astrobiology studies, the remarkable success of the NASA Kepler mission has demonstrated that a large variety of planets are common, with accumulating evidence that Earth-like planets are plentiful. We have no evidence yet for any life beyond Earth, but we anticipate that further robotic exploration of other solar system bodies may yield positive results. These exoplanet discoveries increase our confidence that life may be prevalent and potentially common on other worlds. While we still have much to understand about the development of intelligent life, evidence which favors eventual success for SETI pursuits is mounting.

2. *In a recent article in the Journal of Astrobiology, the SETI Institute Director of Research, Dr. Nathalie Cabrol, proposed a broader, multidisciplinary approach to SETI research, beyond radio and optical modalities. What is your opinion?*

Dr. Cabrol is an astrobiologist. Cabrol's article "*Alien Mindscapes – A Perspective on the Search for Extraterrestrial Intelligence*" discusses the philosophical and sociological aspects of SETI research. I agree with Cabrol's recurrent theme that we should continue to work very hard to see beyond our own anthropocentric experiences in order to remain as open as possible to alternative forms of interstellar communication. Cabrol proposes to integrate multiple disciplines from cognitive sciences, space sciences, life sciences, geosciences, mathematics, and astrobiology, in order to generate strategies and missions for current SETI searches. I am concerned about Cabrol's call for a "unified and universal approach for the search for extraterrestrial life." While I encourage involvement of more scientists researching extraterrestrial intelligence (ETI), it is important to note that major differences exist between the related but distinct studies of SETI and astrobiology. One such difference is the remarkable contrast between provisional knowledge of the subjects of study. For astrobiology, Earth hosts an enormous variety of millions of example life forms, which we can study and draw generalizations about life itself. In contrast, to guide SETI, we only have one such example for intelligent and *technological life*; ourselves.

Many approaches described by Cabrol to investigate communication techniques have already materialized in the SETI community over the last several decades. SETI search strategies are continually refined within the community, and although additional researchers and diversity are warranted and welcomed, we should not dismiss current search strategies. Practical considerations such as existing technologies and abilities drive the ways we carve out our search in the interstellar communication phase space (e.g., frequency regime, detector availability and sensitivity, location in the universe). As the article highlights, even though we have used radio for 50 years and have not detected an ETI signal, we are still very far from achieving a complete search, even at these frequencies. It is therefore difficult to fully assess whether or not we have been thinking about our approach to SETI properly, given that we are far from exhausting our current searches with present-day technological capabilities.

Additional notable differences between astrobiology and SETI research are funding and resources. Astrobiology has benefited from a relatively stable flow of funding, resulting in remarkable strides over a very broad and active range of disciplines. I wholeheartedly agree with Dr. Cabrol that we need more minds and perspectives in SETI research. But I would argue that even more crucial is the need for adequate and reliable funds and resources to conduct our present SETI searches. Instrumental and operational funds for the *search itself* are urgently needed. We have barely begun to search, and numerous other articles prior to this one have addressed many of the same topics and ideas raised. SETI missions have been financially starved and challenged for many decades, and given the state of knowledge and technology today, now is the time to reconsider the US research investment. Cabrol's suggested approach could be interpreted as a call to invest in astrobiology endeavors at the expense of SETI. A balanced research investment portfolio in SETI and astrobiology is a more prudent public policy approach.

3. *How large of a role do NGO's play in the search for life?*

Non-governmental organizations (NGOs) do aid the search for life and astrobiology, and have played a very significant role in maintaining some level of SETI research. Searches for life and for intelligent life require funds to sustain research and community support, as well as technological development of new instrumentation, adequate facilities, and operational funds. One superb example of community advancement is the SETI Institute, which has served as a support hub for both astrobiologists and SETI researchers. SETI Institute in the last decade has provided a base for astrobiologists to draw research grants largely from NASA and NSF. Lack of governmental funding for SETI researchers has taken its toll, with the number of SETI researchers remaining level with very little student training and new enrollment into this research endeavor. The vast majority of research training and scientific community development occurs at national universities, where they receive over 60% of their research and development funds from federal grants. In contrast, universities receive less than 10% of R&D support from NGOs¹.

¹ <http://www.bu.edu/research/articles/funding-for-scientific-research/>

While NGOs do not typically provide support for researchers, they have financed and catalyzed new instrumentation and facilities for SETI programs. The newest example of this is the *Breakthrough Listen* program, which has provided significant resources for securing telescope access and observing time through the Green Bank Telescope, Parkes Telescope, and the Automated Planet Finder at Lick Observatory. In recent years, radio and optical SETI programs have been deployed primarily with assistance from private donors and foundation grants to implement new ideas and search strategies. This has been essential, but the primary reason the SETI research community is so very small is due to lack of reliable, sustainable funding for researchers. Government funding sources like NSF and NASA need Congressional action and appropriations to fund SETI programs. Such programs enjoy substantial public interest and enthusiasm, offer educational opportunities through student and postdoctoral research fellowships, and create potential for profound intellectual payoff.

4. *The largest telescopes available to the scientific community generally fall into two categories: optical and radio. Why does SETI primarily utilize radio telescopes and what are the advantages of each type in the search for extraterrestrial life?*

As previously described in my written testimony, SETI has traditionally been conducted at radio and optical wavelengths. These wavelengths are used today for long-range communication devices on Earth and within our solar system. In addition to our technological maturity in these areas, there are very good reasons for using radio and optical regions of the electromagnetic spectrum to communicate across interstellar distances. First and foremost, electromagnetic radiation (colloquially "light") has the highest speed limit in the universe – it's the quickest and most efficient way to send information. As Einstein taught us, light *is* energy; lower frequency radio waves have lower energy, higher frequency optical light has higher energy. These different energy levels lead to important differences between sending and receiving a signal at radio or optical wavelengths.

Planetary atmospheres are transparent to radio (e.g., radio passes through solid walls), and radio backgrounds from stars and galaxies are relatively faint compared to optical light. To send and detect a distant radio signal we typically need a larger radio telescope (e.g., >100-meter) than an optical telescope (e.g., 1-10-meters). Radio receivers also scan in frequency space for the signal, much like we search for the correct frequency (e.g., 88.5 FM) for a radio station in the car. Optical and infrared telescopes can easily search large swathes of frequencies for a signal, and are not encumbered by scanning over many frequencies like radio. Similarly, the human eye detects optical light and is able to detect simultaneous colors – frequencies – in a single instant.

A radio search is much more likely to chance across relatively less directional low-frequency radio or microwave (radar) alien signals. Radio searches would be able to detect leaked broadcast signals, such as the expanding bubble of radio and TV generated from Earth over the last century. In contrast, optical and infrared lasers are an excellent directional communication method, and have the advantage of generating a powerful and tightly beamed signal that can easily outshine a star by several orders of magnitude in brightness, thus creating a signal distinguishable over vast interstellar distances. Optical and infrared lasers

are also able to efficiently transmit enormous amounts of information. Radio and laser searches thus complement each other, rather than replacing one another. Since we have no way to determine which regime an alien civilization might choose, exploring both regimes in SETI is essential.

5. Does the Arecibo Observatory provide unique capabilities for the search for life?

A variety of radio telescopes nation- and world-wide are designed to conduct different scientific studies. For radio telescopes a trade-off exists between the number of radio frequencies covered, amount of sky observed, and sensitivity or brightness of signal they are able to detect. Arecibo is a large (300-meter) single, fixed radio dish. Deploying instrumentation on Arecibo is more cost effective than doing so on multiple dish radio programs since antennae and feeds are only needed for Arecibo's single dish. The Chinese FAST radio telescope is now the largest single radio dish (500-meter) in the world. But Arecibo will retain its essential and significant advantage of covering a huge range of frequencies from 300 to 10,000 MHz, compared to FAST's very limited coverage of only 1050 to 1450 MHz. The Arecibo frequency range offers a large advantage to SETI searches and also other important scientific programs. For example, Arecibo is essential for the NANOgrav² study which aims to detect gravitational waves using pulsars. Arecibo's unique capabilities are also crucial for determining precise orbits of potentially hazardous near-Earth asteroids. Sustained funding for Arecibo for both of these programs will be crucial over the next several years.

6. Please provide any perspectives you may have on KIC 8462852, commonly known as the "Tabby Star."

The discovery of the unusual light fluctuations of KIC 8462852 or "Tabby's Star" is a perfect example of the importance of new technological development, and participation of citizen science. Without the NASA Kepler science mission, this "typical" main sequence star would have been overlooked and we would have missed detecting this mysterious object. To date there is no evidence which suggests any artificial origin for the brightness fluctuations of the star. SETI facilities at radio, optical, and near-infrared have conducted searches on this source and have received no signals. The best predictions so far explain the unusual dimming being caused by material orbiting the star, such as planetary detritus or debris from the disintegration (perhaps by tidal disruption) of another body in that solar system.

The Kepler mission algorithms were designed to search for transiting extrasolar planets, and these light dips were so unusual that they were missed by the exoplanet transit search routine. It took the dedication of citizen science participants to make this exciting discovery. Tabby's Star highlights the need for data mining on existing astronomical surveys (such as SETI searches, among many others), and should be supported with mainstream NSF and NASA funding. The serendipitous discovery of Tabby's Star also highlights opportunities offered by breaking into new technological realms and phase spaces. An important lesson to SETI researchers is to continue to operate at the forefront of technology and instrumentation.

² <http://nanograv.org/>

and to create innovative new facilities, such as the future radio Square Kilometer Array (SKA) and optical Thirty Meter Telescope (TMT).

7. Please provide your perspectives on the Association of Universities for Research in Astronomy (AURA) proposal for a High-Definition Space Telescope (HDST).

The High-Definition Space Telescope (HDST) is the proposed next-generation space-based optical telescope that offers a collecting area of 12-meters. HDST telescope size would far surpass the collecting area of the optical Hubble Space Telescope (2.4-meters) and the future infrared James Webb Space Telescope (6.5-meters). An increase in telescope size not only boosts sensitivity to see fainter sources, but also increases the ability to see finer image detail (resolution). The latter is vitally important and a major reason for increasing telescope size, and bestows the coin-name "High-Definition" for this exciting future space-based telescope program. The HDST has a diverse range of fundamental astrophysical science goals, ranging from studying distant galaxies in the infant universe, understanding the life cycles of stars, imaging Earth-like planets, and monitoring the surfaces of solar system bodies at unprecedented detail.

An exciting prime directive of HDST is to directly image dozens of Earth-like extrasolar planets and study their atmosphere in great detail, in order to search for water vapor, oxygen, and other organic compounds that could be biomarkers. Extrasolar planet studies are now rapidly moving beyond the mere discovery and statistical evaluation of exoplanets, and toward characterizing the properties of other planets and determining whether they are amenable to life as we know it. This is fundamentally important for SETI searches and astrobiology. A space-based mission that focuses on investigating properties of exoplanetary atmospheres is the next essential step in understanding our place in the galaxy. The HDST resolution will be highly complementary to other ground-based telescope facilities such as the future Thirty Meter Telescope (TMT) and Giant Magellan Telescope (GMT), as well as the current Atacama Large Millimeter Array (ALMA). Coordination between multi-wavelength ground- and space-based telescopes is essential for astrophysical studies, and should remain a valuable consideration for all SETI programs.

Responses by Dr. Christine Jones

**HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON SPACE
SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY**

Astronomy, Astrophysics, and Astrobiology

Dr. Christine Jones, President, American Astronomical Society

Questions submitted by Rep. Brian Babin, Chairman, Subcommittee on Space

Babin 1: Both you and Ms. Meg Urry, the outgoing president, have impressive resumes centered around astrophysics, in your case focusing on X-ray astronomy and in her case, black holes. Is there also expertise on astrobiology, especially exoplanet research, among the leaders of the AAS? What is AAS's agenda with respect to astrobiology?

The AAS leadership has expertise in the areas of astrobiology and exoplanet research. AAS Councilor Nancy Chanover (New Mexico State University) studies the atmospheres of planets in our solar system, specifically Venus, Jupiter, and Saturn. AAS Councilor Stephen Unwin's (JPL) research interests are the detection and characterization of extrasolar planets and the dust disks that trace the formation history of exoplanetary systems. AAS's Division of Planetary Sciences (DPS) President Jason Barnes (University of Idaho) studies the composition of Saturn's moon Titan and exoplanets. DPS Secretary Anne Verbiscer (University of Virginia) and DPS Committee members Carly Howett (Southwest Research Institute) and Julie Castillo-Rogez (JPL) research different aspects of icy bodies in our solar system. DPS Committee member Jani Radebaugh (Brigham Young University-Idaho) focuses on Saturn's moon Titan and Jupiter's moon Io.

With regard to the agenda of the AAS, the AAS supports the community consensus of the New Worlds, New Horizons 2000 Decadal Survey (NWNH) and the Vision and Voyages Planetary Sciences Decadal Survey (V&V), which both include a number of priorities related to astrobiology.

New Worlds, New Horizons:

- WFIRST, the Wide-Field Infrared Survey Telescope, currently planned to include a coronagraph, which will allow for imaging and spectroscopy of nearby exoplanets.
- New Worlds Technology Development Program has helped the community to prepare for a planet-imaging mission beyond 2020.
- Gemini International Partnership includes the opportunity to image exoplanets directly. For example, the Gemini Planet Imager, funded partially by NSF and NASA, is on Gemini South and has directly imaged giant exoplanets.

Vision & Voyages:

- Mars 2020, the next generation Mars rover and the next stage to understanding one of our nearest neighbors in the Solar System.

- Jupiter/Europa clipper, which would orbit Jupiter's moon Europa. Congressional instructions will lead to a lander, which will land on Europa.
- New Frontiers missions that will focus on either Saturn, Venus, the Moon, Jupiter's moon Io, comets, or Trojan asteroids.

Also note that JWST, a priority mission from the 2000 decadal survey, now scheduled for launch in 2018, will have the ability to spectroscopically characterize exoplanets around nearby stars.

In addition, AAS Journals have responded to the community interest in astrobiology and exoplanets by having a publications corridor that focuses on astrobiology and related topics. That publication's corridor is called "The Solar System, Exoplanets, and Astrobiology."

Babin 2: You've stated that the focus of your research has been the analysis of observations from the Chandra X-ray Observatory. As this observatory ends its life cycle, what major advances do you foresee in the field of X-ray spectroscopy?

Fortunately Chandra is still operating well and provides both high angular resolution images and high energy resolution spectroscopy which result in exciting discoveries in all areas of high energy research from studies of the X-ray emission from the polar regions of the planet Jupiter to images of cosmic jets produced by supermassive black holes in high redshift quasars. In addition, since NuSTAR's (Nuclear Spectroscopic Telescope Array) launch in June 2013, scientists have used its measurements in the energy range from 3 to 79 keV to measure the spin rates for black holes, to discover a highly magnetized neutron star near the center of our Milky Way, and to map the distribution of titanium-44 in the Cassiopeia A supernova remnant.

In February 2016, Japan launched the Hitomi satellite, which carried an X-ray calorimeter that would have provided very high-resolution spectroscopy of celestial X-ray sources. Unfortunately the mission failed after completely only one preliminary spectroscopic observation of the Perseus cluster of galaxies.

In the future, ESA (European Space Agency) has chosen the X-ray mission Athena (Advanced Telescope for High Energy Astrophysics) for launch in 2028 to address the questions of how ordinary matter assembles into large-scale structures and how black holes grow and shape the Universe.

The future in the US could see the launch of an X-ray Surveyor in the 2030's. This is just one of the four missions that NASA is currently reviewing for the next decadal survey. The others are a Far-IR Surveyor, a Large UV/Optical/Infrared (LUVOIR) Surveyor, and a Habitable Exoplanet Imaging mission.

Babin 3: Gravitational waves were recently detected at Laser Interferometer Gravitational-Wave Observatory (LIGO). In what ways, if any, do you see this discovery impacting how

we will explore the universe in future decades?

While electromagnetic radiation from radio waves to gamma rays gives us one view of our Universe, particles like neutrinos and cosmic rays provide additional information and gravitational waves provide yet another way to learn about our Universe. Two, likely three, detections of gravitational events due to the merging of stellar mass black holes have been reported by the LIGO team—the second two at our AAS meeting in June. While the positional uncertainties of these events on the sky are very large, in the future, with the addition of other LIGO stations, the ability to locate the detected gravitational events on the sky will be significantly improved. This will greatly improve the possibility of finding an electromagnetic counter-part to the gravitational event. Our array of electromagnetic telescopes are already working in radio, optical/IR, and X-ray wavelengths to narrow down the location of the gravitational events with the goal of identifying the source and providing a detailed description.

Babin 4: Does the Arecibo Observatory provide unique capabilities to use for the search for life, or for near-Earth object tracking and characterization?

Arecibo Observatory has the unique ability to perform radar characterization of asteroids. This radar characterization helps scientists to assess the impact risk of asteroids that we have already discovered. This unique capability is why Arecibo Observatory was considered a higher priority than some other NSF-supported facilities in the 2012 portfolio review. However, declining budgets at NSF's Astronomical Sciences Division (NSF/AST) mean that NSF/AST may not be able to continue its support of Arecibo. This has led to NSF needing to consider options for Arecibo's future. Arecibo Observatory is currently cooperatively supported by NSF/AST, NASA, and NSF's Atmospheric and Geospace Sciences Division.

Babin 5: Please provide any perspectives you may have on KIC 8462852, commonly known as the "Tabby Star."

Sometimes when scientists learn something new it raises questions that we had not thought to ask before. The discovery of KIC 8462852, also known as "Tabby's Star," is one example of that. KIC 8462852 was discovered using the Kepler space-based observatory. In the Kepler observations, the brightness of the star was observed to decrease twice for a few days, each by approximately 15% and 20%; in addition, there have been several other smaller dimmings. The star also appears to be becoming dimmer over time. Even a planet as large as Jupiter passing in front of the star would not cause such a large decline in brightness lasting several days. Because my area of research focuses on the effect supermassive black holes have on their host galaxies, I do not have any unique perspectives on what might be causing Tabby Star's unusual light curve. However, based on the reading that I have done, some likely scenarios are coalescing material falling onto the star or an orbiting cloud of dusty and disintegrating. I would want more observations before reaching a conclusion about the nature of this unusual star.

For more information on possible explanations, I refer you to the original paper "Planet Hunters X. KIC 8462852 - Where's the Flux?" by Tabetha Boyajian and her co-authors.

**HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON SPACE
SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY**

Astronomy, Astrophysics, and Astrobiology

Dr. Christine Jones, President, American Astronomical Society

Questions submitted by Rep. Donna Edwards, Ranking Member, Subcommittee on Space

Edwards 1: In your prepared statement you note the importance of making observations publicly available no more than a year after they are obtained. Can you elaborate on why this is so important to advancing the science?

Edwards 1a: What steps do observatories take to make their data available for use by researchers and the public?

Observations from both ground and space observatories are extremely precious and can often be used to address more than one set of scientific questions, including new questions that were not apparent at the time the original observations were obtained. Indeed, most astrophysical observations are not single use. Significant new science is done with old data. Taking the Hubble Space Telescope as an example, nearly half the papers written in recent years, use old observations obtained from the archives (Figure 1). Similarly, an original Chandra observer may have observed a set of galaxies to study the X-ray emission from supermassive black holes at their centers, while other astronomers may use these same observations to characterize the hot X-ray emitting gas in the haloes of the galaxies or to study the populations of X-ray emitting binary stars in these galaxies.

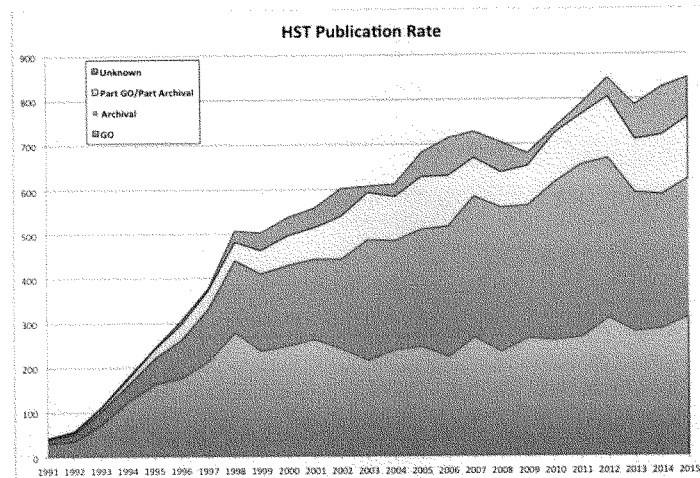


Figure 1 Plot of the number of publications from the Hubble Space Telescope (HST) as a function of year. The source of the data is denoted by the color. Note that the number of publications that used archival data increased over time.

Astronomical archives also allow observations across the electromagnetic spectrum to be combined to investigate all types of astrophysical phenomena. As just one example of how multiple observational archives are used, astronomers use radio observations from the Very Large Array (VLA) archive (<https://archive.nrao.edu/archive/archiveproject.jsp>), HST observations (<https://archive.stsci.edu/hst/>), Chandra X-ray observations (<http://cxc.harvard.edu/cda/>), and ground-based optical observations, e.g., NOAO (<http://archive.noao.edu/search/query>), to explore how powerful jets are produced by supermassive black holes. The availability of archived observations also allows others to reproduce the results, an essential component of scientific inquiry. While different scientists analyzing the same observations usually reach similar conclusions, occasionally they may arrive at a different understanding of the observations. In those cases, having all observations available allows scientists to discuss both the data and their analysis techniques to understand how they arrived at their different conclusions.

Most astronomical facilities now include a significant effort to archive their observations and make that data publicly accessible. The Hubble Space Telescope, the Chandra X-ray Observatory, the Very Large Array (VLA), the NASA/IPAC Infrared Science Archive, and the Sloan Digital Sky Survey (SDSS) are very successful examples of these data archiving efforts. SDSS has become one of the most productive and widely used data sets of all time, both for professional research and through citizen science projects, e.g., GalaxyZoo. And as new surveys, for example from the Large Synoptic Survey Telescope (LSST), become available, our community will continue to improve upon our efforts to make observations and the necessary calibration data and analysis tools available.

The creation and maintenance of observational archives enable the use of archival data and data products by the full community of researchers and students, including those at smaller institutions, which often have more limited resources. As technologies change, it is important that data archives keep up with these changes, so the data sets remain useful. Software tools that allow visualization and analysis of multi-wavelength observations are critical for multi-messenger science. These visualization and discovery tools are critical for supporting multi-wavelength and multi-messenger science. Data archives are most useful when techniques and software needed to support data discovery and visualization are available. Plus, training astronomy students in software and the development techniques for tools and methods not only makes them better researchers, but can also prepare and enable them to explore synergies and techniques that can be applied to other fields that use large data archives.

Edwards 1b: What can be done to make astronomy data more widely available and easy to use?

It is important that observations obtained through federally funded research programs be made publicly available after a limited proprietary period. Even private observatories, with the users being primarily from the observatory's home institution(s), are federally-supported through funding to build the telescope, research grants that provide travel, student support, summer salaries, or publication costs. As a community, we must encourage all ground-based observatories to make all federally funded research data, in both raw and processed forms, publicly available.

Since data collection became digital in the 1980's, the national observatories have had a mission to make data taken with public telescopes widely available after a proprietary period (generally 12 – 18 months). While this began by making raw data public, this now includes other data products such as uniformly reduced and calibrated data from standard pipelines, e.g., Dark Energy Camera (DECam), Dark Energy Camera Legacy Survey (DECaLS), object catalogs and reduced spectra, e.g., SDSS.

To make astronomical data more widely available and easy to use required that we make a choice of a common file format (FITS formats are widely used in astronomy), make observations and related information available through the Internet, and provide appropriate analysis tools (including instructions) for the user. There is free software that can be used to ingest, manipulate and compare large quantities of data. While more sophisticated analysis tools are often required, the publicly available image display system SAOImage/ds9 provides both easy access to many of the NASA mission archival images and simple analysis tools (<http://ds9.si.edu/site/Home.html>) that allow the user to view images from many observatories on the same physical scale on the sky and to extract basic data from the images. These analysis tools and calibration schemes are constantly improving, in many cases because they combine a larger amount of data, e.g., obtained over much longer times than the original calibration.

In summary, to improve the utility of archived observations, the archives must be properly calibrated and easily available, which requires that observatories have calibration and

archival teams to prepare the observations and to advise the users of these observations. These astronomical data archives should be treated as "living" entities, with many downstream data products stemming from the same raw data. This is one reason there must be requirements for the ongoing curation of the data. Another reason is that hardware and software evolve on a time scale shorter than the useful lifetime of data. For both those reasons, the data archive needs to be overseen by knowledgeable scientists. An archive that is stored and left alone is less useful as time passes, and may, at some point, cease to be useful.

For more information about the state and future of data archiving for ground-based facilities, I direct you to Chapter 3: The US OIR System of "[Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System](#)" (National Research Council, 2015).

Edwards 1c: With the emergence of "multi-messenger" astronomy, are there new challenges to data sharing or interoperability?

The primary requirement for data sharing and interoperability is the choice of a common file format (the astronomy community generally uses FITS), a machine accessible archive, and accurate calibration information. One of the major challenges our community must address regarding multi-messenger data is proper calibration of the observatory and the instruments. Proper calibration of observations is challenging as instruments age or when there are sources of outside contamination, e.g., weather conditions or seismic activity. However, properly calibrated data that is made publically available would allow scientists of all types perform a simple analysis to study the intensity variability of a source.

The analysis requires only basic information from a file, e.g., source counts per second, which can be converted into a source flux. When given the distance to the source, one can determine the energy output of the source over the energy band of the instrument used to measure the count rate. Performing this calculation over time allows one to search for flares or regular pulsations.

Edwards 2: Is the United States in danger of losing world leadership in astronomy and astrophysics? If so, what, in your view, are the most important things to do to ensure continued U.S. leadership in astronomy and astrophysics?

There is evidence that the US is losing its leadership in some wavelength ranges and branches of astrophysics. The largest future radio telescope, the Square Kilometer Array (SKA), is being built by a consortium in Australia and South Africa, and the largest low frequency radio telescope (LOFAR) is under construction in Europe. Several of the best scientific instruments and ground-based optical and infrared observatories are operated by the European Southern Observatory.

That said, the development and construction of the Large Synoptic Survey Telescope (LSST) will be important for maintaining US leadership in astronomy. In addition, public-private partnerships, particularly at NSF, have resulted in new cutting edge instrumentation in the wake of significant government budget cuts. These partnerships

have preserved both community access for using new (privately built) instrumentation as well as access to raw data and data products from the private surveys for which the instruments were built. The Dark Energy Camera (DECam) and the Dark Energy Survey at Cerro Tololo Inter-American Observatory (CTIO), an NSF-supported observatory in Chile, are examples. The US also has an opportunity to lead in the exploitation of big data sets and the infrastructure needed to support the data. Good data use infrastructure and software is value-added to any single telescope.

The European Space Agency (ESA) is developing a space-based gravitational wave observatory. While the US-led LIGO project dominates in the ground-based detection of gravitational waves, the US does not currently have plans for a space-based observatory. ESA is also planning to build a next generation X-ray observatory (ATHENA). The 2020 decadal survey will be considering whether the US should build a future X-ray observatory, however it is interesting to note that while X-ray astronomy was basically “invented” by US astrophysicists the next generation of X-ray observatory will not be US-built. For the US to remain a world leader in astronomy and astrophysics future projects, as defined by the decadal survey, must be funded and completed. This will require both the dedication of astronomers willing to lead and work on long-term missions and the continued support of Congress to invest in the technologies needed in the future in several areas of space astrophysics and for Congress to commit to building future flagship missions in several areas of astrophysics.

The US also has an opportunity to lead in the exploitation of big data sets and the infrastructure needed to support the data. Good data use infrastructure and software is value added to any single telescope.

Edwards 3: You serve on the Board of Directors of the Astronomical Society of the Pacific, which is focused on increasing the understanding and appreciation of astronomy by “engaging scientists, educators, communicators, amateur astronomers and the public, to advance science and science literacy.” What is your perspective on the progress being made in engaging the next generation in education and careers in astronomy or STEM in general?

Astronomy has a particular role in attracting young people to science. It is natural for humans gazing at the night sky to wonder what is out there and how it came to be. Frequently, astronomy is the first post-high school science class a student takes, often leading to further study in science and math. Even though only a small fraction of students turned on by astronomy make it their profession, astronomy training provides valuable skills in quantitative analysis, big data, and computing, to mention just a few. That said, there are challenges in engaging the next generation in STEM, but these are not unique to astronomy. Recruiting, training, and retaining quality STEM K-12 teachers are vital components to facilitating students’ interest and engagement in STEM fields. Ensuring that these teachers have adequate lines of communication to scientists by supporting the education and public outreach activities at science agencies like NASA and NSF is necessary. In recent years, these lines of communications have become more complicated by restructuring the education and public outreach activities within Federal agencies. Removing some of these boundaries would allow scientists to more efficiently

engage students.

Astronomy has not been a required part of the national K-12 curriculum, so many students receive little exposure to astronomy through public schools. This is improving with the advent of the National Science Framework and Next Generation Science Standards (NGSS). But astronomy, space science, and aerospace engineering are given little emphasis in these documents.

For the US to remain competitive in the global community, we must act to prepare the next generation of STEM professionals, including astronomers and aerospace engineers. Astronomy is entering an age of great discovery. We are finding new exoplanets on a daily basis, a new generation of telescopes will be available for use, the existence of gravity waves has been confirmed, and we are elucidating the nature of dark matter and dark energy. We are also entering a new age of space exploration through the private endeavors of companies like SpaceX and Virgin Galactic.

Astronomy is more diverse and inclusive than it was in the past, but the field is still predominately white and male. Our community is making real improvements in the participation of underserved and traditionally underrepresented groups in the astronomical sciences.

In my personal opinion, there are several steps Congress can take to facilitate interest and engagement in STEM fields such as astronomy. These include:

- 1) Increase funding to NSF to support research and development on best practices in astronomy education specifically. This includes funding for K-12 science teacher professional development and pre-service programs, the development of exhibits and programs bringing astronomy research results and methods to museums and planetariums, and the development of out-of-school programs that bring astronomy experiences to after school programs, libraries, national parks, and other public venues.
- 2) Advocate to include astronomy content in grades K-12. Astronomy is by its very nature multidisciplinary. It requires understanding of basic physics, chemistry, biology, and geology. The National Science Framework (and NGSS) requires that students understand big ideas in science and to think across traditional disciplinary boundaries. Astronomy is the perfect vehicle for this kind of learning, which mirrors the way modern science is actually practiced.
- 3) Increase funding to NASA education projects. Currently, NASA funds a portfolio of extremely innovative astronomy education projects through recent Cooperative Agreement Notices (CANS). These projects need sustained support, including funds for science teacher professional development efforts, which were not included in the last round of CANS.
- 4) Work closely with members of organizations like ASP and AAS who specialize in STEM and astronomy education and have national experience that is both deep and broad to improve the STEM pipeline so that students are provided with technical

and quantitative skills and can move between STEM fields.

Appendix II

ADDITIONAL MATERIAL FOR THE RECORD

DOCUMENTS SUBMITTED BY SUBCOMMITTEE ON SPACE
CHAIRMAN BRIAN BABIN

ASSOCIATION OF UNIVERSITIES FOR RESEARCH IN ASTRONOMY, INC.



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**OPERATING FOR THE
NATIONAL SCIENCE FOUNDATION**

Gemini Observatory
La Serena, Chile & Hilo, Hawai'i

Large Synoptic Survey Telescope
Tucson, Arizona & La Serena, Chile

National Optical Astronomy Observatory
Tucson, Arizona & La Serena, Chile

National Solar Observatory
Boulder, Colorado & Maui, Hawai'i
Sunspot, New Mexico & Tucson, Arizona

**OPERATING FOR THE NATIONAL AERONAUTICS
AND SPACE ADMINISTRATION**

Space Telescope Science Institute
Baltimore, Maryland

MEMBERS/SINCE:

Boston University 1993
California Institute of Technology 1972
Carnegie Institution of Washington 1997
Cornell University 2016
Fisk University 2010
Georgia State University 2008
Harvard University 1957
Indiana University 1957
Instituto de Astrofísica de Canarias 2005
Iowa State University 1992
Johns Hopkins University 1982
Kiepenheuer-Institut für Sonnenphysik 2016
Massachusetts Institute of Technology 1981
Michigan State University 1997
Montana State University 2005
New Jersey Institute of Technology 2010
New Mexico State University 1999
Ohio State University 1957
Pennsylvania State University 1998
Pontificia Universidad Católica de Chile 1997
Princeton University 1959
Rutgers University 1999
Stanford University 2012
Stony Brook University 1986
Swinburne University 2008
Texas A & M University 2014
Tohoku University 2010
Universidad de Chile 1982
University of Arizona 1972
University of California Berkeley 2007
University of California Santa Cruz 1987
University of Chicago 1957
University of Colorado 1977
University of Florida 2002
University of Hawaii 1978
University of Illinois 1980
University of Maryland 1986
University of Michigan 1957
University of Minnesota 1995
University of North Carolina at Chapel Hill 1995
University of Pittsburgh 2012
University of Texas at Austin 1972
University of Toledo 2016
University of Virginia 2003
University of Washington 1986
University of Wisconsin 1957
Vanderbilt University 2010
Yale University 1958

July 11, 2016

Hon. Lamar Smith
House Committee on Science, Space, and Technology
2321 Rayburn House Office Building
Washington, DC 20515

Hon. Eddie Bernice Johnson, Ranking Minority Member
House Committee on Science, Space, and Technology
2321 Rayburn House Office Building
Washington, DC 20515

Dear Chairman Smith and Hon. Johnson,

On behalf of the Association of Universities for Research in Astronomy (AURA), I commend you for holding a hearing to examine the connections between astrophysics, astronomy, and astrobiology. Because of your support, NASA has the most exciting and inspiring space science program in its entire history.

Each time a new telescope has turned to the skies, unanticipated discoveries have opened windows onto revolutionary vistas. With just a 2-inch diameter telescope, Galileo discovered Jupiter's moons and helped establish that Earth is not the center of the Universe. Centuries later, the *Hubble Space Telescope* turned its 2.4-meter mirror towards a seemingly blank patch of the sky to reveal a hidden universe of faint galaxies. This "Hubble Deep Field" proved there must more than a hundred billion galaxies in the universe.

And yet, some of humanity's most compelling questions remain unanswered: Are we alone in the universe? Are other Earth-like worlds common? Do any have signs of life? How did life emerge from a lifeless cosmic beginning? Curious humans have asked these questions for millennia, but for the first time we can foresee actually answering them. We now know that planets around other stars (exoplanets) are abundant. Tantalizing evidence suggests that Earth-like exoplanets may be habitable, with conditions similar to our Earth.

Ultimately, the grand challenge of the search for life elsewhere will require the full commitment of NASA, the scientific community, and perhaps even the emerging private sector space program. In terms of astronomy and astrophysics, however: with the right telescope we can soon *search nearby exoplanets for signs of life, and tell the cosmic story of how this life came to be.* This is astrobiology writ large.

ASSOCIATION OF UNIVERSITIES FOR RESEARCH IN ASTRONOMY, INC.

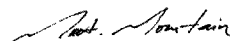
Ambitious goals require careful plans. AURA (charged with promoting excellence in astronomical research by providing community access to state-of-the-art facilities) therefore commissioned a study of how a new space telescope could revolutionize ultraviolet and optical astronomy in the era following the James Webb Space Telescope (JWST) mission. AURA specifically tasked a world-class team of scientists and technologists to “assess future space-based options ... that can significantly advance our understanding of the origin and evolution of the cosmos and the life within it.” The committee concludes that a space telescope equipped with a 12-meter mirror can find and characterize *dozens* of Earth-like planets, and at the same time make transformational advances across nearly all fields of astrophysics.

In their report entitled “From Cosmic Birth to Living Earths,” these scientists and engineers developed an audacious yet responsible concept for the *High Definition Space Telescope*, taking into account all the lessons learned from JWST (see attached Executive Summary; the full report is available at HDSTvision.org). NASA is now studying this concept in more detail.

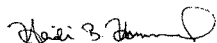
As we celebrate Hubble’s 26th year in orbit, we find ourselves at a unique moment in human history: the confluence of scientific discovery, technology, and our leadership in international space capabilities make possible a space telescope that can determine whether life has arisen elsewhere in the cosmos, and at the same time make transformational advances across nearly all fields of astrophysics. The discovery of life on an Earth-like world will have at least as profound an impact in our 21st century society as the Apollo moon landings had in the last century. Discovery of life elsewhere would be a tipping point in human history, and this is the kind of scientific and human exploration vision we believe is worthy of our great space agency.

With adequate planning, technology development, and strong leadership, such a telescope could be available in the next two decades. We thank you for the opportunity to share our excitement about the search for life elsewhere.

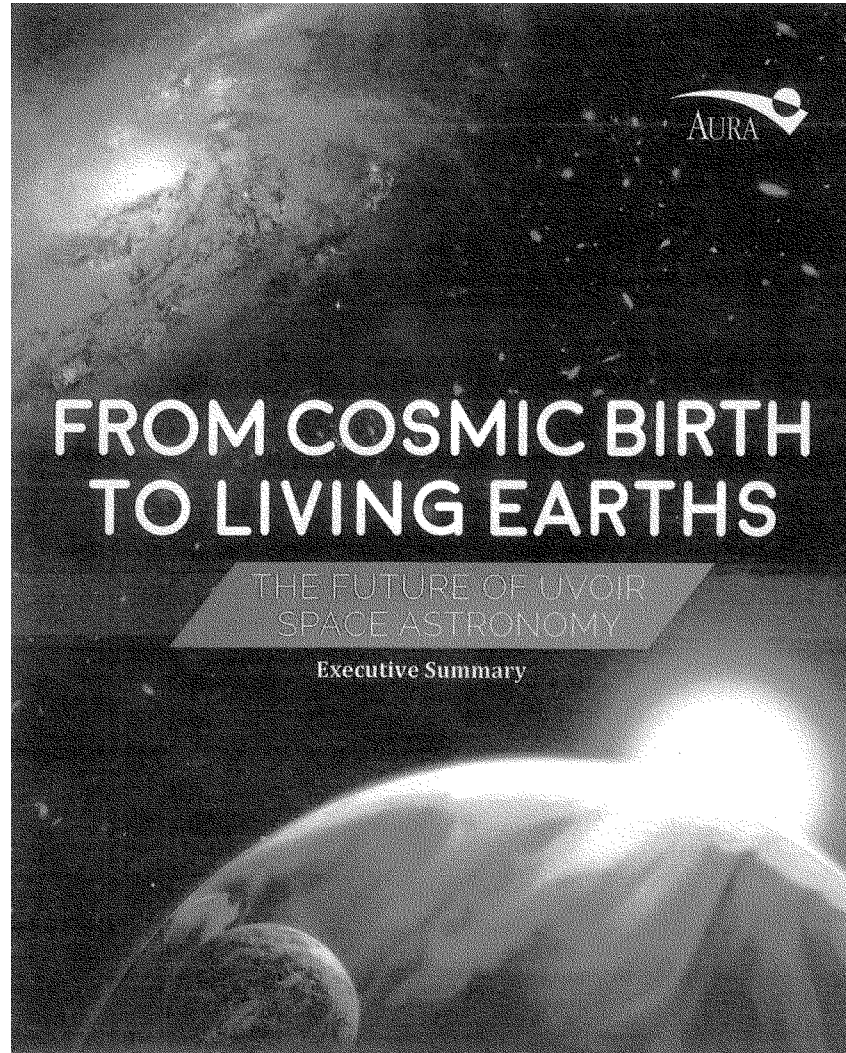
Sincerely,



Matt Mountain
AURA President



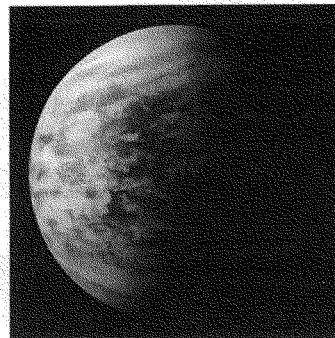
Heidi B. Hammel
AURA Vice President



EXECUTIVE SUMMARY OF THE AURA REPORT:
 "FROM COSMIC BIRTH TO LIVING EARTHS: THE FUTURE OF UVOIR SPACE ASTRONOMY"

The High Definition Space Telescope

Each time a new telescope has turned to the skies, unforeseen discoveries have opened windows onto revolutionary vistas. With only a primitive 2-inch diameter telescope, Galileo discovered Jupiter's moons and helped establish that Earth is not the center of the Universe. Four centuries later, the *Hubble Space Telescope* turned its 2.4-meter mirror towards a seemingly blank patch of the sky (the Hubble Deep field) and revealed a hidden universe of faint galaxies, proving that there must be upwards of a hundred billion galaxies in the visible Universe. And yet, with centuries of discoveries behind us, some of humanity's most compelling questions remain unanswered: Are we alone in the Universe? Are other Earth-like worlds common? Do any have signs of life? How did life emerge from a lifeless cosmic beginning? Curious humans have asked these questions for millennia, but for the first time we can foresee actually answering them. With the right technology, and the right telescope, we could soon search nearby exoplanets for signs of life, and tell the cosmic story of how this life came to be.



An artist's rendition of the exoplanet Kepler-69c, which is 1.7 times larger than the Earth. Credit: NASA/Ames/JPL-Caltech.

Ambitious goals require careful plans. The Association of Universities for Research in Astronomy (AURA) — charged with promoting excellence in astronomical research by providing community access to state-of-the-art facilities — therefore commissioned a study of how a new space telescope could revolutionize ultraviolet (UV) and optical astronomy in the era following the *James Webb Space Telescope's* mission¹. AURA tasked a team of scientists and technologists to "assess future space-based options ... that can significantly advance our understanding of the origin and evolution of the cosmos and the life within it." The committee concludes that a space telescope equipped with a 12-meter primary mirror can find and characterize dozens of Earth-like planets and make transformational advances across nearly all fields of astrophysics. The concept is called the *High Definition Space Telescope*.

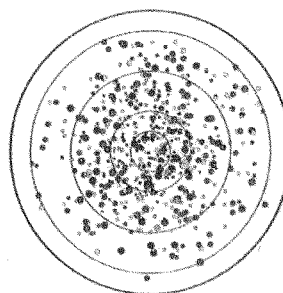
The High Definition Space Telescope (HDST) would be sensitive to light at UV through near-infrared wavelengths, viewing the universe from the second Earth-Sun Lagrange point (L2), one million miles from the Earth. Its segmented mirror would be folded into either a current or future heavy-lift rocket, before being launched and deployed at its final home. In its mission to discover and study Earth-like planets orbiting Sun-like stars, HDST will directly image exoplanets — including

¹ Plans for NASA's next major space telescope, *WFRST/AFTA*, do not include UV capability.

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planets that may be as much as 10 billion times fainter than their host star — by carefully suppressing the star's light. *HDST's* exquisite image quality at visible wavelengths (with more than 25 times the resolving power of the *Hubble Space Telescope*) and high sensitivity all the way into the ultraviolet part of the spectrum (100 times more sensitive than *Hubble*), combined with a versatile set of imaging and spectroscopic instruments, will trigger profound breakthroughs in astrophysics. Like *Hubble* and *JWST*, *HDST* would operate as a general observatory, supporting a broad range of investigations beyond its core exoplanet mission.

HDST's primary goal is to find and characterize dozens of Earth-like exoplanets. A sample of dozens of exoEarths opens up the opportunity to identify truly Earth-like worlds with rocky surfaces and oceans, amidst a complex zoo of other varieties of terrestrial planets. With this large sample, observing telltale signs of life in the planets' atmospheres becomes possible. If life is rare, *HDST* will take us from our current complete ignorance of the occurrence rate of inhabited worlds to a first constraint, potentially showing how remarkable our own existence is. If life is common, a large sample of terrestrial worlds with highly unusual atmospheric chemistry will secure our belief that life of some kind exists beyond the Earth, regardless of possible false positives. Whatever the outcome, *HDST* will change how we see our place in the Universe.



A map of the nearly 600 stars that would be surveyed with *HDST* to find dozens of exoEarths, given approximately two years of observing time. The stars are plotted on a projection of a sphere with radius 35 parsecs. Star colors and sizes correspond to star type and relative luminosity. Only a large 12-m telescope can survey hundreds of stars to find dozens of exoEarths.

While thousands of exoplanets are already known to exist, none are yet known to be truly Earth-like, even though some have radii similar to Earth's. Distinguishing habitable worlds like Earth (i.e., those with surface water oceans) from greenhouse planets like Venus, or barren worlds like Mars, requires understanding a planet's atmosphere. *HDST* will therefore not just image new worlds, but will also acquire spectra of their atmospheres at visible (and in some cases out to near-infrared) wavelengths to search for signs that indicate a potential planet like our own.

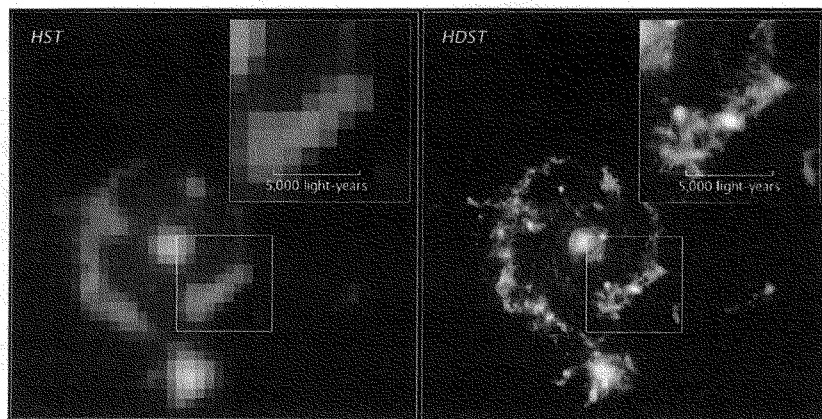
HDST will search for exoEarths around hundreds of stars, but during that quest will revolutionize the study of planetary systems in general. *HDST* will discover planets of all sizes, and any surrounding debris disks. Such discoveries will not only place detected exoEarths in context within their own planetary systems, but are also interesting in their own right.

While the search for the exoEarths that are waiting to be discovered is compelling, the search is not easy. Not only are these planets intrinsically faint, they also orbit

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very bright host stars. Viewed from another star, our Earth's reflected light would be 10 billion times fainter than the Sun itself, with an orbit that separates the Earth from the Sun by a tiny fraction of an arcsecond. These challenges can be overcome if *HDST* meets three significant goals. First, *HDST* must have a large primary mirror area both to gather enough photons (exoEarths are as faint as the faintest objects in the Hubble Deep Field) and to cleanly separate the planet and star for hundreds of star systems, many of which are tens of parsecs² away. Second, *HDST* must have exquisite starlight suppression that blocks out the starlight to 1 part in 10 billion for planet-star projected separations of about 35 milliarcseconds (equivalent to the width of a human thumb viewed from a distance of 130 km). Third, *HDST* must be thermally and dynamically stable for this starlight suppression to perform at the needed level.

Major advances in all areas of astrophysics are possible with HDST. A telescope with *HDST*'s degree of sensitivity, resolution, and stability will transform current understanding of how galaxies, stars, and planets form and evolve. With its high-definition resolving power, *HDST* has the amazing ability to take an optical image or spectrum at about 100-parsec spatial resolution or better, *for any observable object in the entire Universe*, no matter where a galaxy lies within the cosmic horizon. This 100-parsec threshold is the scale of individual star forming regions and dwarf satellites—the constituent building blocks of galaxies.



The 5× gain in angular resolution from *Hubble* (left) to *HDST* (right) is demonstrated in this simulated image of a galaxy 10 billion light-years away. *Hubble* detects the galaxy's bulge and disk but only *HDST* resolves the galaxy's star forming regions and its nearby dwarf satellite.

The fields of astrophysics that *HDST* will impact are too vast to list. But as a small sample, *HDST* will transform studies of the most distant bodies within our own Solar

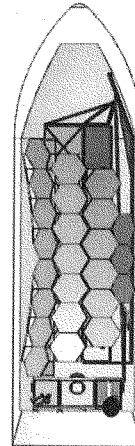
² One parsec is equal to 3.26 light-years or 3.08×10^{13} km.

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System, elucidate complex chemistry within the nearest stellar populations, robustly measure of the masses of new stars, map panoramic high-resolution images of star formation in the vicinity of supermassive black holes, and trace detailed motions within the smallest, dark-matter-dominated galaxies. *HDST* will make the first maps of the nearly invisible material permeating the cosmic web and fueling the growth of galaxies, thanks to its unprecedented collecting area, its 100× gain in ultraviolet sensitivity over *Hubble*, and its novel multiplexed instrument modes. These same abilities will allow *HDST* to trace the recycling of heavy elements from stars to intergalactic space and back, to follow the origins of stellar masses, characterize the composition of planet-forming disks, and to monitor geysers on satellites of the outer planets. In many of these studies, *HDST* will operate in tandem with the next generation of 30-meter ground-based telescopes, in much the same way that *Hubble* and 10-meter telescopes operate cooperatively today.

In short, *HDST* promises dramatic gains in the survey volume, spatial resolution, and sensitivity of any astrophysical study, especially if it can operate its wide-field imaging cameras and spectrographs in parallel during long, staring exoplanet observations. In this mode, every observation of an exoEarth could be transformed into a new equivalent of the *Hubble* Ultra Deep Field, but one that takes hours instead of ten days to acquire. The information embedded in this data set would exceed any presently existing or contemplated survey.

HDST is poised to capitalize on a rich heritage in space telescope technology. Although visionary in its goals, *HDST*'s technologies are well within reach. Starting with the *Hubble Space Telescope* (launch 1990) and including the *Spitzer Space Telescope* (2003), the *James Webb Space Telescope* (2018), and *WFIRST/AFTA* (a wide-area survey telescope to be launched in the 2020s), existing technologies provide a firm foundation to build on when scaling to the size and performance level required by *HDST*. These technologies include deployment of segmented apertures, thermal and dynamical stabilization, starlight suppression, precision pointing, wavefront control, and panoramic, high performance photon detectors. *HDST* will also benefit from technological developments in the commercial world, and from investments made by other countries and other government agencies, providing options for *HDST* in areas of detectors, electronics, structural materials, metrology systems, mechanisms, and large lightweight mirrors. The report carefully analyzes the needed technologies, and lays out a pathway that can bring them rapidly to the final state of maturity. By investing early in advancing starlight suppression for a telescope like *HDST*, and in broader supporting technologies, there is a path forward that can lead to a flight-ready *HDST* design within the near future.



HDST folded within an EELV or SLS-1 shroud.

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HDST will operate at much warmer temperatures than *JWST*. This difference will allow *HDST* to utilize lower-cost optical materials, incur less thermal stress in the structures, simplify component and system design, manufacturing and qualification, and lower the costs of system integration and testing, much of which had to be done under cryogenic conditions for *JWST*.

The report lays out recommendations for meeting HDST’s key engineering challenges. The first priority is to develop *high-contrast coronagraphs* for *HDST*. A coronagraph blocks the light from a star to enable direct detection of the planets orbiting the star. An onboard coronagraph will have the efficiency needed to search for exoEarths around hundreds of stars. *HDST’s* science goals constrain the many performance requirements that such a coronagraph must meet. Another type of starlight suppression instrument is called a starshade – a free-flying specially-shaped occulter that casts its shadow on a telescope many thousands of km away. Although starshades are not part of the *HDST* baseline mission, they provide a vital alternative architecture, and could be employed in a second phase of the mission to enable more detailed characterization of interesting planetary systems.

The second-highest priority recommendation is to address *segmented-mirror system technologies*, including the mirrors, structure and mounts. The key issues are thermal and dynamic stability, but also important are: optical performance, mirror mass density, and efficiency of manufacture. Mirror substrate technologies are mature and in use now, but the other elements of the mirror systems—active thermal control, actuation, low vibration mounts and supports, etc.—are less so.

High observatory *throughput from the UV into the near-infrared* is also a top priority. This goal requires investment in instrument and detector technologies to optimize their efficiency, particularly for observations in the UV.

HDST in context. *HDST* has the potential to push back the frontiers of astrophysics with a single great observatory. Rather than small focused missions that have a shot at finding one to a few exoEarths (while relying on unusually good fortune to turn up signs of life on even one), or that specialize in a particular subfield of astrophysics, *HDST* pursues the more ambitious approach. *HDST’s* sensitivity, resolution, and efficiency of exoplanet characterization make it a profoundly capable mission. It can deliver a high yield of exoEarths along with a rich database of information about all kinds of planetary systems. At the same time, and often while observing in tandem with exoEarth searches, *HDST* will fundamentally change our understanding of the Universe throughout cosmic time. Many fields of astronomy will be transformed by its capabilities; none will remain entirely untouched. *HDST* will transform how we all—scientists and public alike—see our place in the universe.

Arecibo Science Advocacy Partnership

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11th July 2016

To: Congressional Committee on Science, Space & Technology
 Regarding: The NSF/NASA-supported Arecibo Observatory in Puerto Rico

We are writing as the Board of the Arecibo Science Advocacy Partnership (ASAP, <http://www.areciboscience.org>), an organization of 150 scientist-users of Arecibo, representing its three major disciplines and including many of the most prominent and distinguished scientists using the Observatory. We write in concern that actions may be taken to curtail or close this unique and crucial US scientific facility.

AO Highlights—

- AO operates the most sensitive radio telescope, planetary radar, and incoherent scatter radar (ISR) on the planet.
- AO is uniquely powerful for planetary and Near-Earth-Object (NEO) radar. AO and the Green Bank Telescope (GBT) can, as in the past, be paired for unique new observations particularly of Near-Earth Objects (NEOs). The UHF radar combined with Haystack or the GBT could find use for very near NEOs.
- AO's great sensitivity is required for prominent US science, such as gravitational wave detection and analysis. Single dishes provide key advantages over arrays for certain work. The capabilities of AO and the GBT are highly complementary —and the loss of either would cripple leading areas of US astronomical research.
- The new ionospheric modification facility combined with AO's radars and optical instruments opens a new era in active plasma physics experimentation.
- The most sensitive ISR in the world combined with metals lidar (K, Na, Ca, Ca+, and Fe from resonant scattering), other optical instruments, and the VHF radar make AO the premiere facility for studying the role of meteoroid flux metals in the upper atmosphere and ionosphere.
- AO remains a unique public education model, with even greater future potential.
- One of AO's principal strengths is its flexibility to adapt quickly to new science and techniques, a capability rapidly being lost on other more complex and/or array instruments configured towards certain fixed science goals.
- AO will not be superseded importantly by FAST (Five hundred meter Aperture Spherical Telescope in China), which will not have any planetary or atmospheric radar facility, nor will it be able to observe at frequencies above 2 GHz.
- AO is one of the prime research facilities in Latin America and the Caribbean.
- A representative broad array of leading AO science activities is discussed in the ASAP Whitepapers (<http://www.areciboscience.org>).

Arecibo's three main scientific research areas are interdependent and mutually supportive. ASAP strongly asserts the synergy of the three science areas at AO. No one could be curtailed or abandoned to strengthen others or reduce operating costs.

Contact: Arecibo Science Advocacy Partnership,
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Arecibo from Earth orbit ©DigitalGlobe
*...Unique in the Solar System, and
 a beacon in our region of the Galaxy...*