NASA'S NEXT FOUR LARGE TELESCOPES

HEARING

BEFORE THE

SUBCOMMITTEE ON SPACE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

ONE HUNDRED FIFTEENTH CONGRESS

FIRST SESSION

DECEMBER 6, 2017

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December 6, 2017

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NASA'S NEXT FOUR LARGE TELESCOPES

Wednesday, December 6, 2017

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

The Subcommittee met, pursuant to call, at 2:41 p.m., in Room 2318 of the Rayburn House Office Building, Hon. Brian Babin [Chairman of the Subcommittee] presiding.

LAMAR S. SMITH, Texas
CHAIRMAN

EDDIE BERNICE JOHNSON, Texas
RANKING MEMBER

Congress of the United States
House of Representatives

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
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NASA's Next Four Large Telescopes

Wednesday, December 6, 2017
2:00 p.m.
2318 Rayburn House Office Building

Witnesses

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

Ms. Cristina Chaplain, Director, Acquisition and Sourcing Management, U.S. Government Accountability Office

Mr. A. Thomas Young, Former Director, Goddard Space Flight Center, NASA; Former President and Chief Operating Officer, Martin Marietta Corporation

Dr. Matt Mountain, President, Association of Universities for Research in Astronomy

Dr. Chris McKee, Professor Emeritus of Astronomy, Physics, University of California, Berkeley, on behalf of the National Academies of Sciences, Engineering and Medicine

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

Charter

TO: Members, Committee on Science, Space, and Technology
FROM: Majority Staff, Committee on Science, Space, and Technology
DATE: December 6th, 2017
SUBJECT: Space Subcommittee Hearing: "NASA's Next Four Large Telescopes."

On Wednesday, December 6, 2017 at 2:00 p.m. in Room 2318 of the Rayburn House Office Building, the Committee on Science, Space, and Technology, Subcommittee on Space, will hold a hearing titled, "NASA's Next Four Large Telescopes."

Hearing Purpose

The purpose of this hearing is to examine the development of the Transiting Exoplanet Survey Satellite (TESS), the James Webb Space Telescope (JWST), the Wide Field Infrared Survey Telescope (WFIRST) and the planning for a next generation space telescope.

Witnesses

- **Dr. Thomas Zurbuchen**, Associate Administrator, Science Mission Directorate, National Aeronautics and Space Administration
- **Ms. Cristina Chaplain**, Director, Acquisition and Sourcing Management, U.S. Government Accountability Office
- **Mr. A. Thomas Young**, Former Director, Goddard Space Flight Center, NASA; Former President and Chief Operating Officer, Martin Marietta Corporation
- **Dr. Matt Mountain**, President, Association of Universities for Research in Astronomy
- **Dr. Chris McKee**, Professor Emeritus of Astronomy, Physics, University of California, Berkeley, on behalf of the National Academies of Sciences, Engineering and Medicine

Staff Contact

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

Chairman BABIN. The Subcommittee on Space will now come to order. Without objection, the Chair is authorized to declare a recess of the Subcommittee at any time. Welcome to today's hearing entitled "NASA's Next Four Largest Telescopes." I would now like to recognize myself for five minutes for an opening statement.

In May of this year, the primary mirror for the James Webb Space Telescope arrived in Houston, which is in my district at JSC, for a final round of cryogenic testing, just in time for the hurricane season.

These components started a 100-day testing session in a vacuum chamber at the Johnson Space Center, where three truckloads a day of liquid nitrogen and cold helium gas chilled the telescope to minus 233 degrees Celsius. That's a total of 300 trucks just for one test.

Well, I'm told that Hurricane Harvey complicated things by washing out the roads so bad that they had to improvise a new route to get the trucks to the test facility. I am very proud of the fine job that the folks at JSC did working around the clock to ensure the test was a success. I know firsthand the hardships that are being experienced in Houston due to the hurricane, Hurricane Harvey, and I pray that the recovery for everyone there is going as well as can be expected given the conditions. I would like to add, too, that the new continental rainfall record is in my district of 51.88 inches and an unofficial record of 64-plus inches.

While the 2017 hurricane season has been challenging, this year has been an exciting time for astrophysics. The Nobel Prize in Physics was awarded to three citizens, three Americans, that developed the Laser Interferometer Gravitational-wave Observatory, or LIGO, which made the first-ever direct observation of gravitational waves, ripples in the fabric of space and time, that were predicted by Albert Einstein 100 years ago.

I understand several of the potential witnesses for today's hearing could not attend because they are in Stockholm at the prize celebrations. I'd like to congratulate these fine Americans for their outstanding discoveries.

Our nation is proud of these achievements. Images from the Hubble Space Telescope are some of the most iconic in history. And we look forward to what is to come from even more capable missions like the Wide-Field Infrared Space Telescope, WFIRST.

It has been mentioned to me that with Hubble you could take a single picture into a meeting to show what was discovered, but with WFIRST you'll have to wallpaper their entire office. The capability has increased 100 times since Hubble.

WFIRST is a critical new flagship mission, and we need to make sure that it stays on course. The assets provided to NASA from the National Reconnaissance Office seem like a good fit for the mission, but the program needs reasonable timelines and a realistic budget.

It is worth noting that several years ago this Committee proposed that NASA study WFIRST to determine if the assets from NRO would be appropriate for this mission and whether it would cost more to repurpose existing hardware than to build the observatory from the ground up. Now we face additional questions about the appropriate scope of the mission.

The recent report from the independent review committee on WFIRST laid out several options for reining in the cost. And I'm particularly interested to learn more about what impact reducing capability will have on the cost, but more importantly, on the science.

I was pleased to see NASA's Request for Information, or an RFI, announcement on October 12th seeking input from private parties interested in operating the Spitzer Space Telescope and executing the Spitzer science program. NASA is looking for partners to continue operating the space telescope on their own dime after the NASA mission is completed. I applaud this type of innovative approach, and I hope to see more thinking like this in the future.

NASA is currently conducting large- and medium-mission concepts studies for the 2020 Decadal survey. New concepts like in-space assembly, in-space servicing, and taking advantage of the proposed Deep Space Gateway when developing architectures for very large space telescopes could offer tremendous new capabilities.

However, Congress needs to understand the status of the programs today as well as the plan going forward. Decisions made now can have long lasting implications on future missions.

It seems the smaller principal investigator, or PI, that lead missions generally do well at budgeting, scheduling, and cost containment. We need to know that there isn't a systematic or fundamental programmatic problem with how we plan and execute these larger strategic missions.

And I am thankful that our witnesses are here today to help us better understand where we are with these programs and how we plan to move forward. And I very much look forward to hearing your testimony.

[The prepared statement of Chairman Babin follows:]

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

For Immediate Release
December 6, 2017

Media Contacts: Thea McDonald, Brandon VerVelde
(202) 225-6371

Statement from Brian Babin (R-Texas)
NASA's Next Four Telescopes

Chairman Babin: In May of this year, the primary mirror for the James Webb Space Telescope, or JWST, arrived in Houston for a final round of cryogenic testing. Just in time for hurricane season.

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It is worth noting that several years ago this committee proposed that NASA study W-FIRST to determine if the assets from NRO would be appropriate for the mission and whether it would cost more to repurpose existing hardware than build the observatory from the ground up. Now we face additional questions about the appropriate scope of the mission.

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However, Congress needs to understand the status of the programs today, as well as the plan going forward. Decisions made now can have long lasting implications on future missions.

It seems the smaller Principle Investigator, or PI, lead missions generally do pretty well at budgeting, scheduling and cost containment. We need to know that there isn't a systematic or fundamental programmatic problem with how we plan and execute these larger strategic missions.

I am thankful that our witnesses are here today to help us better understand where we are with these programs, and how we plan to move forward. I look forward to your testimony.

###

Chairman BABIN. I would like to now recognize the Ranking Member, the gentleman from California, Mr. Bera, for his opening statement.

Mr. BERA. Thank you, Mr. Chairman, and thank you for having another incredibly interesting hearing. And I look forward to learning a lot from the witnesses.

I think we can all, you know, remember as children, you know, just kind of laying on our backs in our backyards or wherever we were, gazing up at the sky. And even to this day, you know, on clear evenings, I'll go out and lay and just gaze up at the stars. And my daughter will sit there and say, Dad, what are you doing out there? And it's the mystery of what's out there. What can we discover? What don't we know? That is exciting. And you know, it's something that piques our curiosity.

And you know, you can see a lot with the naked eye, but you know, really you could see a lot more with the advancements we've made in our telescopes, starting in 1990 with the Hubble Space Telescope. What we've been able to discover in these last two decades has been pretty remarkable. Hubble helped scientists pin down the age of the universe, showed us some of the most distant galaxies that we've ever observed. You know, the Compton Gamma Ray Observatory created the first-ever all sky map of gamma radiation. The Chandra x-ray Observatory revealed the first-ever observations of a supernova remnant. These are all pretty exciting.

You know, if you take Hubble, Chandra, and Spitzer, all provided recently the observations of the neutron star merger detected via gravitational waves by LIGO. Again, pretty remarkable what we are discovering.

So I think this is a very timely hearing as we start to think about, you know, the next technologies and observatories that let us look into our origins as well as what is out there. You know, in March 2018, TESS is going to be launched which will build on the success of the Kepler mission to conduct the first all-sky survey transiting exoplanets from space.

You know, the Chairman talked about James Webb, which will follow Hubble as the next great space observatory but with 100 times the sensitivity of Hubble. Again, what are we going to discover with that and how does that continue to propel us forward? We're in the first early stages of the WFIRST program and looking at where that will take us. But it will give us a much larger field of view to advance the science of dark energy and exoplanets. Again, you know, what is out there? Answering that question, and you know, hoping to propel another generation of folks like myself to just gaze and wonder and enter the fields of science.

And you know, we're talking about the next four missions. So as we start to think about that fourth mission, how do we learn from the missions that have preceded it? And how do we make sure we engage in an open process, you know, following the Decadal Survey, looking at that and, you know, really build on what we've learned, make sure we're using all of our resources responsibly but that we're objectively choosing what that next mission would be?

So again, I'm pretty excited about this hearing. I think it builds on what I think is the best subcommittee in Congress and certainly the most interesting subcommittee in Congress. And with that, I'll yield back.

[The prepared statement of Mr. Bera follows:]

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

House Committee on Science, Space, and Technology
Subcommittee on Space
"NASA's Next Four Large Telescopes"
December 6, 2017

Good afternoon and welcome to our distinguished panel of witnesses. Thank you, Mr. Chairman, for holding this hearing on "*NASA's Next Four Large Telescopes*". Before the advent of space telescopes, astronomers were forced to peer through Earth's atmosphere in order to study the cosmos. While the atmosphere is crucial for the survival of life on Earth, it has long been an annoyance for astronomers. The atmosphere is turbulent and can block certain wavelengths of light from ever reaching the ground – making some astronomical objects and phenomena invisible to ground-based observers.

Starting with the launch of the Hubble Space Telescope in 1990, NASA's Great Observatories program greatly expanded our view of the cosmos. Hubble helped scientists pin down the age of the universe and showed us some of the most distant galaxies ever observed. The Compton Gamma Ray Observatory created the first-ever all-sky map of gamma-ray radiation. The Chandra X-ray Observatory revealed the first ever observations of a supernova remnant. Finally, the Spitzer Space Telescope gave us the first ever detection of light emitted by an exoplanet.

In August of this year, Hubble, Chandra, and Spitzer all provided observations of the neutron star merger detected via gravitational waves by LIGO. This marked the first time an astronomical object was studied using the combination of electromagnetic radiation and gravitational waves. We truly are in the era of multi-messenger astronomy.

NASA's Great Observatories revolutionized the way we view our place in the cosmos. Now, NASA is building on the successes of these telescopes with the Transiting Exoplanet Survey Satellite, the James Webb Space Telescope, and the Wide-Field Infrared Survey Telescope.

- Planned for launch in March 2018, TESS, a medium class mission, will build on the success of the Kepler mission to conduct the first all-sky survey of transiting exoplanets from space.

- JWST will follow Hubble as the next great space observatory, but with 100 times the sensitivity of Hubble. JWST's expected launch date of October 2018 was recently delayed as much as eight months.

- WFIRST will produce images that rival the detail of Hubble, but with a much larger field of view to advance the science of dark energy and exoplanets. Unlike TESS and JWST, WFIRST is at an early stage of development.

NASA is also reviewing four mission concept studies in preparation for the 2020 astronomy and astrophysics decadal survey that will recommend the next high-priority space telescope. We have representation from one of those candidate mission concepts here today and I hope to hear from NASA about the science potential of <u>all four</u> missions being studied in preparation for the decadal survey.

Clearly, the advantages of placing sophisticated observatories in space are plentiful. However, developing telescopes that can operate in space comes with technological and programmatic challenges. We are all eager to learn from JWST's challenges, and to discuss what actions will be needed to maintain the overall programmatic balance of NASA's astrophysics portfolio.

While NASA must continue to carry out complex, high-priority missions, it must also ensure that the small- and medium-scale missions are adequately supported along with the research that undergirds advances in astronomy. A balanced NASA astrophysics program is critical to maximizing the science return on investment. I hope to hear your thoughts on how NASA can best take lessons learned from past and current missions in order to benefit its future space telescopes in a balanced portfolio.

Well, we have a lot to talk about, and I look forward to hearing from our witnesses. Thank you and I yield back.

Chairman BABIN. Thank you, and I do agree. I now recognize the Chairman of our Full Committee, the gentleman from Texas, Mr. Smith.

Chairman SMITH. Thank you, Mr. Chairman. I appreciate both your comments and the Ranking Member's comments, particularly when you all pointed out that this is a fascinating subject for the American people. They are just riveted by what's going up in space, particularly telescopes that they can see and that are tangible.

I might ask the Ranking Member if he would extend his description of this being his favorite subcommittee to the Science Committee being his favorite Full Committee or not. Maybe? Oh, okay. We'll take any suggestions.

Mr. Chairman, space-based observations from telescopes like the Hubble Space Telescope have amazed us for decades and expanded our understanding of the universe. We have also seen a rapid increase in the exciting discoveries of planets outside our own solar system.

We have confirmed over 3,500 exoplanets and another 4,000 unconfirmed planetary candidates since 1995. Scientists estimate that as many as 11 billion rocky, Earth-sized exoplanets could be orbiting in the habitable zones of Sun-like stars in our own Milky Way galaxy alone.

NASA's next four space telescopes will give us new ways to search for exoplanets and potential signs of life. Each one is designed to build on each other's success.

It's an exciting time for astrophysics. The Transiting Exoplanet Survey Satellite, or TESS, is being prepared for launch next year. The James Webb Space Telescope, or JWST, is only a couple of years away from launch. The Wide Field Infrared Survey Telescope, or WFIRST, program is well underway. And we are now in the early stages of designing the next generation space telescope that will hopefully answer many more of our questions about the universe. In January 2016, NASA initiated the four Decadal survey Mission Concept Studies for the next space telescope that would launch in the 2030s.

With the coming heavy lift capability of the Space Launch System, a future space telescope larger than James Webb could be possible. SLS could enable the launch of telescopes that could scan exoplanets for signatures that indicate the presence of continents, oceans, atmospheres, habitable conditions and perhaps even life itself.

The National Academy of Sciences is preparing to undertake their 2020 Astronomy and Astrophysics Decadal survey. The survey will help inform the Academy about options for future missions.

As fascinating as this all sounds, the space program is hampered by delays. James Webb recently encountered additional problems during testing that will delay the mission to as late as June 2019. An independent review board for WFIRST concluded the project is "not executable" without additional funding or scaling back the mission. And TESS, while still on schedule and budget, experienced a focal shift within the optics of its four wide-angle telescopes during testing that may degrade the science it conducts. The issues with JWST are not insignificant; however, NASA expects the existing James Webb budget to be able to accommodate the change in launch date and that there will not be an impact on the planned science observations. The remaining work will focus on integrating and testing the instruments, telescope and spacecraft to prepare it for its new launch date in 2019.

More troubling is the report on WFIRST. An independent outside committee established by NASA found that various changes made to WFIRST since it was first proposed as the top-ranking flagship mission in the 2010 Astrophysics Decadal survey created additional costs and technical difficulties. Apparently NASA has not learned lessons from its past experiences. After an extensive re-planning effort due to excessive cost growth, NASA had to constrain James Webb in 2012 to a congressionally mandated cost-cap of $8 billion. Now WFIRST may be subjected to a similar limitation. We cannot allow unbudgeted cost to occur on WFIRST the same way it did on James Webb. The impact to other science missions, as well as other activities at NASA, would be too great. Much better program management and discipline are required to ensure that this does not continue to occur.

Last month NASA instructed the WFIRST program to modify the current design to reduce costs to an earlier target of $3.2 billion. I am hopeful that the program will find creative solutions to maintain the mission's science objectives. NASA must remain mindful that any potential cost increase of WFIRST will put pressure not only on other astrophysics mission, but also on other agency priorities. NASA should continue to explore options to reduce the costs of these large programs, such as leveraging program surpluses, early-stage cost-caps, and firm fixed-price contracts which will benefit taxpayers.

Partnerships between the private and public sector in astronomy are well established, and these ties need to be strengthened when it comes to space telescopes. Going forward, I hope that NASA, space companies, and academia will work together to expand public-private partnerships.

We are on the cusp of something very significant for humanity. But we are still at the beginning. Many more amazing discoveries await us. Going forward, Congress needs to have the necessary confidence in NASA and its contractors to put us on the right path at a reasonable cost.

I look forward to our witnesses' testimony today. With representation from NASA, the National Academy of Sciences, the Association of Universities for Research in Astronomy, the Government Accountability Office, and renowned leaders in the field, we have the opportunity to hear a number of valuable perspectives.

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

[The prepared statement of Chairman Smith follows:]

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

For Immediate Release
December 6, 2017

Media Contacts: Thea McDonald, Brandon VerVelde
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Statement from Lamar Smith (R-Texas)

NASA's Next Four Telescopes

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Chairman BABIN. Yes, sir. Thank you. Now, I'd like to recognize the Ranking Member of the Full Committee, the gentlewoman from Texas, Ms. Johnson.

Ms. JOHNSON. Thank you very much, Mr. Chairman, and a good afternoon and let me welcome our witnesses.

This hearing that's being held on NASA's Next Four Large Telescopes is timely. And today we will receive an update on three telescopes that are likely to revolutionize our understanding of the cosmos. Two of those telescopes, JWST and WFIRST, were the top recommendations of the National Academies' widely respected and highly influential Decadal survey process, which was pioneered by the astronomy and astrophysics community in 1964.

Each of these independent Decadal surveys has involved hundreds of scientists and resulted in an independent, peer-reviewed set of recommended science goals and missions to guide NASA's astrophysics program for the next decade. Importantly, the Decadal survey has also consistently recommended that federal investments be made in a way that ensures a balance is maintained between support for large, medium, and small missions and the research that turns data from those missions into new knowledge. While the Decadal survey process is not perfect, it is this independent, consensus-based process that has been critical to ensuring that Congress supports the priorities established by the astronomy community rather than missions favored by some parties.

That is why Congress, in successive NASA Authorization Acts, has consistently directed that NASA's science programs be based on Decadal survey priorities. Most recently, the 2017 NASA Authorization Act directs NASA to set science priorities by following the guidance provided by the scientific community through the National Academies of Sciences, Engineering, and Medicine's Decadal surveys. The recommendations of the 2010 astronomy and astrophysics Decadal are particularly important as NASA works to determine the appropriate scope of the WFIRST mission. I commend NASA for taking the time to undertake an independent review to assess the alignment of this mission to the Decadal survey's guidance and to the goal of ensuring the overall balance of the astronomy program.

In addition, I look forward to hearing about the progress NASA is making on its next space telescopes. I am glad to hear that NASA is preparing for the upcoming astronomy and astrophysics Decadal survey by conducting four large mission concept studies for the Decadal committee to consider during its deliberations.

And I note that we only have representation from one of the four candidate mission concepts here today. I look forward to hearing about the other three mission concepts as well, today or in the future, because I am sure they are equally as fascinating. Of course, it is ultimately the role of the National Academies and not the Congress to deliberate the science promise of each of these mission concepts.

So I look forward to the witnesses, and I yield back the balance of my time.

[The prepared statement of Ms. Johnson follows:]

<u>OPENING STATEMENT</u>

Ranking Member Eddie Bernice Johnson (D-TX)

House Committee on Science, Space, and Technology
Subcommittee on Space
"NASA'S Next Four Large Telescopes"
December 6, 2017

Good afternoon, and welcome to our witnesses.

Thank you, Mr. Chairman, for holding this hearing on NASA's Next Four Large Telescopes. Today we will receive an update on three telescopes that are likely to revolutionize our understanding of the cosmos. Two of those telescopes, JWST and WFIRST, were the top recommendations of the National Academies' widely respected and highly influential decadal survey process, which was pioneered by the astronomy and astrophysics community in 1964. Each of these independent decadal surveys has involved hundreds of scientists and resulted in an independent, peer-reviewed set of recommended science goals and missions to guide NASA's astrophysics program for the next decade.

Importantly, the decadal survey has also consistently recommended that federal investments be made in a way that ensures a balance is maintained between support for large, medium, and small missions and the research that turns data from those missions into new knowledge. While the decadal survey process is not perfect, it is this independent, consensus-based process that has been critical to ensuring that Congress supports the priorities established by the astronomy community rather than missions favored by some parties. That is why Congress, in successive NASA Authorization Acts, has consistently directed that NASA's science programs be based on decadal survey priorities. Most recently, the 2017 NASA Authorization Act directs NASA to "set science priorities by following the guidance provided by the scientific community through the National Academies of Sciences, Engineering, and Medicine's decadal surveys."

The recommendations of the 2010 astronomy and astrophysics decadal are particularly important as NASA works to determine the appropriate scope of the WFIRST mission. I commend NASA for taking the time to undertake an independent review to assess the alignment of this mission to the decadal survey's guidance and to the goal of ensuring the overall balance of the astronomy program. In addition, I look forward to hearing about the progress NASA is making on its next space telescopes. I am glad to see that NASA is preparing for the upcoming astronomy and astrophysics decadal survey by conducting four large mission concept studies for the decadal committee to consider during its deliberations.

I note that we only have representation from <u>one</u> of the four candidate mission concepts here today. I look forward to hearing about the other three mission concepts, today or in the near future, as well because I am sure they are equally fascinating. Of course, it is ultimately the role of the National Academies, and not Congress, to deliberate the science promise of each of these mission concepts.

I look forward to our witness' testimony. Thank you, and I yield back.

Chairman BABIN. Thank you. I'd like to introduce our witnesses. The first is Dr. Thomas Zurbuchen, and he is Associate Administrator of Science Mission Directorate at NASA. He earned both his Master's of Science degree and his Ph.D. in Physics from the University of Bern in Switzerland. Thank you for being here today.

Ms. Cristina Chaplain, good to have you, our second witness today. She is Director of Acquisition and Sourcing Management at the U.S. Government Accountability Office. She received a Bachelor's degree in International Relations from Boston University and a Master's degree in Journalism from Columbia University. Welcome.

Mr. A. Thomas Young, our third witness, is former Director at NASA's Goddard Space Flight Center as well as former President and Chief Operating Officer of Martin Marietta Corporation. Mr. Young earned both a Bachelor's degree in Aeronautical Engineering and a Bachelor's degree in Mechanical Engineering from the University of Virginia and a Master's of Management degree from MIT. Welcome to you.

Our fourth witness today is Dr. Matt Mountain, President of the Association of Universities for Research in Astronomy. He received his degree in Physics as well as his Ph.D. in Astrophysics, both from the Imperial College of Science and Technology, University of London. Welcome to you.

And our last witness today is Dr. Chris McKee, Professor Emeritus of Astronomy and Physics at the University of California at Berkeley. He is testifying on behalf of the National Academies of Sciences, Engineering and Medicine. He received his Bachelor's of Arts degree from Harvard and his Ph.D. in Physics from the University of California in Berkeley. Welcome to you.

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

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

Dr. ZURBUCHEN. Thank you. Members of the Subcommittee, I'm pleased to be here today. I want to remember that over 70 years ago, Dr. Lyman Spitzer wrote the first scientific paper that explained the practical advantages of putting large telescopes into space. Dr. Spitzer's dream for large space telescopes was born in the aftermath of World War II and more than a decade ahead of Sputnik. His dream led to a series of NASA-built space telescopes of increasing size and capability, including one that now bears his name. However, it has not been easy. Placing increasingly capable and complex telescopes in the cold vacuum of space is challenging. Some of NASA's early orbiting telescopes suffered from launch failures. Others had on-orbit issues which limited their lifetime. Several cost more than originally planned. But many were groundbreaking successes and transformed how we look at the universe.

NASA has a long history of undertaking large space telescopes that involve significant risk but include monumental advances in our understanding of the universe and our place in it. Hubble was the first of NASA's observatories. Working together, and in concert with ground-based observatories, these large space telescopes have rewritten textbooks and inspired young people in the U.S. and around the world to study science, technology, engineering, and mathematics, like myself.

Along with constructing and operating large facility space telescopes, NASA conducts more frequent smaller-scale missions principal investigator, PI, led within the Explorer Program. The combination of PI-led missions and large space telescopes have achieved some amazing results. One example is the study of exoplanets already mentioned. Thanks to the PI-led Kepler Space Telescope mission, we now know that planets orbiting outer stars are very common.

Next up is TESS, already mentioned, which was selected in 2013 as an Astrophysics Explorer. TESS's mission is to discover those nearest planetary systems that have the highest potential for follow-up characterization using telescopes such as Webb and WFIRST. TESS is currently undergoing integration and testing and is on track to meet its launch-readiness date in March 2018. An unexpected issue encountered during development was a slight focus shift of the cameras during low-temperature testing. This was due to a previously unknown, low-temperature behavior of a material that was used in other spacecraft. The TESS science team has determined that TESS can achieve its science requirements with that shift, and we look forward to its launch next year.

We're also eagerly awaiting the launch of the James Webb Space Telescope in 2019. Webb will be the most powerful space telescope ever built, kept extremely cold by a tennis court-sized sun shade in order to detect the infrared light from very faint, distant objects.

Webb passed a major milestone with the end of cryogenic testing in November at NASA's Johnson Spaceflight Center in Houston. The test showed that the mission is meeting its required performance levels. And I really want to also thank the teams at Johnson which continued the testing in the onslaught that was already described earlier.

The sun shield and spacecraft bus experienced delays during their integration and testing at Northrop Grumman. Following a schedule assessment of the remaining activities, the Webb launch date was changed from October 2018 to between March and June 2019. And as already mentioned, the existing program budget accommodates the change of that launch date.

After Webb, NASA's next great observatory will be WFIRST. Its purpose is to survey large swaths of sky to provide detailed information on the expansion history of the universe and conduct a large-scale search for exoplanets using gravitational lensing of the light of background stars. In addition, WFIRST will carry a technology demonstration coronagraph instrument designed for the detailed analysis of such exoplanets.

In 2016, the National Academy mid-term report affirmed WFIRST scientific promise but cautioned against allowing the cost of the WFIRST mission to affect the balance of missions and research in NASA's portfolio. Based on the report's recommendation, I commissioned an independent technical management and cost assessment of the project. Upon completion of this independent assessment this fall, I directed the team to find reductions in scope and complexity sufficient to return to the cost estimate, the target set at the beginning of the project. I look forward to seeing the redesigned WFIRST mission concept in February.

Thinking beyond WFIRST, we have initiated four concept studies for the next great observatory, and I'd be happy to discuss them further. But our understanding of the universe is much richer than it was for the early pioneers of space astrophysics. Our children are looking at the universe differently than we did when we were kids, and this is due to the investment this body has made over the years. And we're deeply grateful for your support.

I really look forward to answering any questions that you may have.

[The prepared statement of Dr. Zurbuchen follows:]

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Statement of

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

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

Chairman Babin, Ranking Member Bera, and Members of the Subcommittee, I am pleased to have the opportunity to appear before you to discuss the space telescopes currently under development at NASA and those under consideration for the future.

Spitzer's paper

Over 70 years ago, Dr. Lyman Spitzer wrote the first scientific paper that explained the practical advantages of putting a large telescope in space. Dr. Spitzer's dream for large space telescopes was born in the aftermath of WWII, more than a decade before Sputnik became the first human-made satellite to orbit the Earth, 12 years before NASA was established, and 22 years before humans first set foot on the Moon. His dream helped captivate a generation of astrophysicists and led to a series of NASA-built space telescopes of increasing size and capability, including one that now bears his name.

What we do is hard

We have made dramatic strides since 1968, when NASA launched the Orbiting Astronomical Observatory 2 (OAO-2), the first operational space telescope. However, it has not been easy. What we do is and remains hard. Placing increasingly large, increasingly capable and complex telescopes in the cold vacuum of space is very challenging and requires many technological and scientific breakthroughs. Along the way we have experienced many successes and also some failures. Some of NASA's early orbiting telescopes suffered from launch failures, others had on-orbit issues which limited their lifetime, several cost more than originally planned, but many were ground-breaking successes and built up a deep reservoir of scientific data and technical capabilities.

Large Space Telescopes

NASA has a long history of undertaking large space telescopes that involve significant risk but provide monumental advances in our understanding of the universe and our place in it. By their nature, each of these large space telescopes demands capabilities that have never before been put in space, requiring the development of multiple new technologies.

Dr. Spitzer's dream was realized in April 1990 when the Hubble Space Telescope was launched into space aboard the Space Shuttle Discovery. Despite some well-known, early on-orbit issues, Hubble has achieved truly civilization-changing science – it has redefined our understanding of the universe, explored the most distant parts of the cosmos, and revealed to us many wonders and mysteries. Servicing of Hubble by NASA's astronauts has extended Hubble's lifetime well beyond the initial estimate of 15 years, allowing its instruments to be upgraded and further expanding the science it enabled. In its 27 years of operations, Hubble has, among its many stunning accomplishments: measured the age of the universe, revealed the dark energy that is accelerating the expansion of the universe, shown that galaxies formed less than 500 million years after the Big Bang, proved that massive black holes reside at the core of every galaxy, discovered new moons around Pluto, revealed how stars are born and how stars die, detected water and other atmospheric constituents of planets outside of our solar system, observed a comet smashing into Jupiter, and – of course – provided iconic images of galaxies, nebulae, star-forming regions, and solar system planets.

Great observatories and & international partners

Hubble was the first of NASA's four Great Observatories that spanned the electromagnetic spectrum: since 1990, Hubble has been observing the universe in ultraviolet/visible/near-infrared light; the Compton Gamma Ray Observatory (which operated from 1991 to 2000) observed the universe in gamma rays; the Chandra X-ray Observatory (launched in 1999) continues to observe the universe in X-rays; and the Spitzer Space Telescope (launched in 2003) is observing the universe in the infrared. Working together, and in concert with ground-based observatories, these large space telescopes have rewritten the astronomy and astrophysics textbooks, proven technologies that later telescopes have used, and inspired young people around the world to study science, technology, engineering, and mathematics (STEM). Each of these Great Observatories sponsors a guest investigator program that allows the best scientists in the United States to contribute in advancing our understanding of the universe. In part, because of these telescopes and the research they enabled, the United States is considered the scientific leader in the world.

All of these observatories are fundamentally developed in partnership with the American private sector. The set of capabilities in industry and academia determines the scientific capabilities within reach for each generation of telescope, and the technological demands of each telescope advances the state of private-sector capabilities that will be available for future observatories and future applications.

Collaboration on missions with international partners creates additional scientific opportunities. Hubble includes contributions from the European Space Agency (ESA). Compton had contributions from Germany, the Netherlands, and the European Space Agency. Chandra has contributions from Germany and the Netherlands. Spitzer has significant synergies with NASA's SOFIA (Stratospheric Observatory for Infrared Astronomy) airborne observatory, which has major contributions from Germany. The large space telescopes led by NASA's international partners with substantial NASA contributions that are currently in development are ESA's Athena (slated for launch in 2028) and LISA (Laser Interferometer Space Antenna, 2034) missions. Additionally, NASA is partnering on smaller space telescopes including ESA's Euclid (2020) mission and Japan's XARM (X-ray Astronomy Recovery Mission, 2021). Athena is an x-ray mission that will study the evolution of most of the matter in the universe as well as the hot plasma in clusters of galaxies. LISA is a space-based gravitational wave observatory that will listen for the gravitational wave signatures of the mergers of supermassive black holes; it will build on the recent LIGO (Laser Interferometer Gravitational-Wave Observatory) gravity-wave observations of stellar-mass black hole and neutron star mergers. Euclid is a visible/near-infrared mission that will survey the expansion history of the universe. XARM will use a NASA-provided high-resolution x-ray spectrometer to map the matter near black holes and in other extreme environments. Each of these partner-led missions complements existing and planned NASA observatories, and participating in their development speeds the rate at which we can expand our understanding of the universe together.

Small & Medium telescopes

Along with constructing and operating the large facility telescopes as strategic missions, NASA conducts frequent missions on a smaller scale that today are Principal Investigator (PI) led missions within the Astrophysics Explorers Program. Astrophysics Explorers have focused scientific objectives and use mature technologies to ensure fast-paced development at low cost. The Explorers Program has provided dozens of small-to-medium space telescopes and astrophysics observatories since its inception in 1958. Successful Explorer-class missions like Copernicus (OAO-3), Uhuru (SAS-1), IUE (International Ultraviolet Explorer), IRAS (Infrared Astronomical Satellite), COBE (Cosmic Background Explorer), and EUVE (Extreme Ultraviolet Explorer), to name just a few, opened new windows to the universe, filled in key gaps in our knowledge, or completed initial surveys that would inform the observing programs of later telescopes. For example, COBE and WMAP (Wilkinson Microwave Anisotropy Probe) measured cosmological parameters of the early universe that complement Hubble observations of the modern universe and set the stage for cosmological studies with the James Webb Space Telescope (Webb) and WFIRST (Wide Field Infrared Survey Telescope). The combination of multiple telescopes aids our understanding of the changing rate of expansion of the universe over its history as well as the evolution of its structure from the chaos of the Big Bang to the familiar and highly structured clusters of galaxies that we see today.

In addition to the direct scientific return, small missions provide numerous opportunities for young scientists and engineers to gain experience with all aspects of the development and operation of space astronomy missions, making them essential for training the leaders of future large space telescope projects.

Opportunities for astronomers to propose Explorer missions are being offered every two or three years, as recommended by the National Academy of Sciences 2010 Decadal Survey in Astronomy and Astrophysics. The most recent selections were IXPE (Imaging X-ray Polarimetry Explorer) in January 2017, which will measure the polarization of x-rays to reveal the inner workings of energetic processes such as the production of jets by black holes, and GUSTO (Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory) in March 2017, which will conduct a balloon-borne survey of the interstellar material from which new solar systems form. In August, six Explorer mission proposals—three for Medium-Class Explorers and three for Missions of Opportunity—were selected for development as concept studies. One of each will be downselected in 2019 to proceed through development and launch. The next call for Small Explorers and Missions of Opportunity is expected during the spring of 2019.

Exoplanet Research, including Spitzer & TRAPPIST-1
The combination of PI-led missions and large space telescopes achieve some amazing results; advances in the study of exoplanets are just one example. Even as recently as 1995 (five years after Hubble launched), the only known exoplanets were found in science fiction novels. From antiquity through 95 percent of the twentieth century, people wondered and dreamed about life beyond Earth without knowing whether planets orbiting other stars were common or rare. This changed with the discovery of the first exoplanet in 1995, and our knowledge of exoplanets has exploded in the last 20 years. Thanks to pioneering discoveries made with ground-based observatories, followed by the PI-led Kepler Space Telescope mission (launched in 2009), we now know that planets orbiting other stars are common, with over 3,500 confirmed exoplanets. Thirty of these exoplanets are small and rocky like the Earth (having a size of 2 Earth radii or less) and are found in the habitable zone, the area around the parent star where liquid water can exist on the surface of a rocky planet.

In February 2017, NASA's Spitzer Space Telescope revealed the first known system of seven Earth-sized planets around a single star. This exoplanet system is called TRAPPIST-1, named for the Transiting Planets and Planetesimals Small Telescope (TRAPPIST) in Chile. In May 2016, researchers using TRAPPIST announced they had discovered three planets in the system. Assisted by several ground-based telescopes, including the European Southern Observatory's Very Large Telescope, Spitzer confirmed the existence of two of these planets and discovered five additional ones, increasing the number of known planets in the system to seven. Three of these planets are firmly located in the habitable zone. That discovery set a new record for greatest number of habitable-zone planets found around a single star outside our solar system. All of these seven planets could have liquid water – key to life as we know it – under the right atmospheric conditions; however, the chances are highest with the three planets in the habitable zone. At about 40 light-years (235 trillion miles) from Earth, this system of planets is relatively close to us.

Spitzer, an infrared telescope that trails Earth as it orbits the Sun, is well-suited for studying TRAPPIST-1 because the star glows brightest in infrared light, light whose wavelengths are longer than the eye can see. In the fall of 2016, Spitzer observed TRAPPIST-1 nearly continuously for 500 hours. Spitzer is uniquely positioned in its orbit to observe enough crossing of the planets in front of the host star (known as "transits") to reveal the complex architecture of the system. Engineers optimized Spitzer's ability to observe transiting planets during Spitzer's "warm mission," which began when the telescope's coolant ran out as planned after the first five years of operations.

More observations of the system are sure to reveal more secrets. Following up on the Spitzer discovery, NASA's Hubble Space Telescope has initiated the screening of four of the planets, including the three inside the habitable zone. These observations aim at assessing whether the planets have puffy, hydrogen-dominated atmospheres, typical for gaseous worlds like Neptune.

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In August 2017, NASA-funded researchers published research that provides a good estimate for the age of the TRAPPIST-1 system, concluding that the TRAPPIST-1 star is quite old: between 5.4 and 9.8 billion years. This is up to twice as old as our own solar system, which formed some 4.5 billion years ago; in theory, the TRAPPIST-1 star could be almost as old as the universe itself.

Because the TRAPPIST-1 system has persisted for billions of years, the planets had to evolve together, otherwise the system would have fallen apart long ago. That said, it is unclear what this older age means for the planets' habitability. On the one hand, older stars flare less than younger stars, and recent research confirmed that TRAPPIST-1 is relatively quiet compared to younger ultra-cool dwarf stars. On the other hand, since the planets are so close to the star, they have soaked up billions of years of high-energy radiation, which could have boiled off atmospheres and large amounts of water. In fact, the equivalent of an Earth ocean may have evaporated from each TRAPPIST-1 planet except for the two most distant from the host star.

In our own solar system, scientists using NASA's MAVEN (Mars Atmosphere and Volatile Evolution Mission) spacecraft have discovered that Mars is an example of a planet that likely had liquid water on its surface in the past, but lost most of its water and atmosphere to the Sun's high-energy radiation over billions of years. However, old age does not necessarily mean that a planet's atmosphere has been eroded. Since the TRAPPIST-1 planets have lower densities than Earth, it is possible that large reservoirs of volatile molecules such as water could produce thick atmospheres that would shield the planetary surfaces from harmful radiation. A thick atmosphere could also help redistribute heat to the dark sides of these tidally-locked planets, increasing habitable real estate. But this could also backfire in a "runaway greenhouse" process, in which the atmosphere becomes so thick the planet surface overheats – as on Venus. More research is needed.

<u>TESS</u>

Our more general search for exoplanets continues and we are on the precipice of the next great leap forward, with TESS, Webb, and WFIRST on the horizon. Next up is the Transiting Exoplanet Survey Satellite (TESS), which was selected in 2013 as a PI-led Astrophysics Explorers mission. It will search for planets around nearby stars using the same method that the Kepler space telescope successfully employed to determine how frequently planets exist in other solar systems. TESS's mission is to discover transiting planetary systems around the nearest and brightest stars, which are exactly those planetary systems which have the highest potential for follow-up characterization studies. To carry out this mission, TESS will conduct a two-year all-sky survey, monitoring 500,000 bright stars to find transiting planets that orbit them. That catalog of planets will provide many of the best targets for study by other telescopes, including Webb and WFIRST.

Many of the stars that TESS observes will be smaller than our 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 through transit spectroscopy. Exoplanets orbiting the nearest stars are the best candidates for direct imaging using a coronagraph, such as the one that WFIRST will have.

The TESS spacecraft is currently undergoing final integration and testing, and it is on track to meet a launch-readiness date in March 2018. The most significant issue encountered during this phase of development was a slight unexpected focus shift of the cameras detected during low-temperature testing. The shift was due to a previously unknown low-temperature behavior of a material that has been used in many other spacecraft. Analysis has shown that the focus shift improved TESS ability to detect planets in the center of its field-of-view and decreased the ability to detect planets in the outer edges of the field-of-view. The TESS science team has determined that TESS can achieve its Level 1 science requirements with the focus shift, and we look forward to its launch and initial science operations next year. The scientific community is well-prepared to exploit TESS's observations because their techniques and tools follow from those used for analysis of Kepler data.

Webb

We also eagerly await the launch of the James Webb Space Telescope in 2019 to probe deeper into the origins of the universe, to detect the first stars and galaxies that formed in the early universe, and to carefully examine the makeup of known exoplanets through both transit spectroscopy and direct imaging. Webb was the top priority of the 2000 Decadal Survey for Astronomy and Astrophysics. Webb is NASA's next great observatory and will be the most powerful space telescope ever built, carrying out science investigations for thousands of astronomers worldwide. The 6.5 meter (21 foot) diameter infrared-optimized telescope is designed to study an extremely wide range of astrophysical phenomena: the first stars and galaxies that formed; star forming regions in nearby galaxies; the atmospheres of nearby exoplanets; as well as objects within our own solar system. Webb is an international project led by NASA in collaboration with our partners ESA and the Canadian Space Agency (CSA). With much greater sensitivity, Webb will be able to detect the chemical fingerprints of water, methane, oxygen, ozone, and other components of a planet's atmosphere when it transits in front of its parent star. Webb also will allow the analysis of planets' temperatures and surface pressures – key factors in assessing their habitability.

Testing of the telescope and science instruments went very well. Webb passed a major milestone when the vault-like, 40-foot diameter, 40-ton door of Chamber A at NASA's Johnson Space Center in Houston was unsealed on November 18, signaling the end of the telescope's cryogenic testing. Scientists and engineers at Johnson put Webb's optical telescope and integrated science instrument module through a series of tests designed to ensure the telescope functioned as expected in an extremely cold, airless environment akin to that of space. These tests included an important alignment check of Webb's 18 primary mirror segments, to make sure all of the gold-plated, hexagonal segments acted like a single, monolithic mirror. Engineers and scientists are currently analyzing the data from this months-long test. This was the first time the telescope's optics and its instruments were tested together, although the instruments had previously undergone cryogenic testing in a smaller chamber at NASA's Goddard Space Flight Center. Engineers from Ball Aerospace, Harris Space and Intelligence Systems, Northrop-Grumman, as well as staff from the Space Telescope

Science Institute (STScI) and our foreign partners worked alongside NASA personnel for the test at Johnson.

The Webb telescope team persisted with the testing even when Hurricane Harvey slammed into the coast of Texas on August 25 as a category 4 hurricane before stalling over eastern Texas and weakening to a tropical storm, where it dropped as much as 50 inches of rain in and around Houston. Many Webb telescope team members at Johnson endured the historic storm, working tirelessly through overnight shifts to make sure Webb's cryogenic testing was not interrupted. In the wake of the storm, some Webb team members, including team members from STScI and Harris, volunteered their time to help clean up and repair homes around the city, and distribute food and water to those in need.

While Webb was inside the chamber, insulated from both outside visible and infrared light, engineers monitored it using thermal sensors and specialized camera systems. The thermal sensors kept tabs on the temperature of the telescope, while the camera systems tracked the physical position of Webb to see how its components very minutely moved during the cooldown process. Monitoring the telescope throughout the testing required the coordinated effort of every Webb team member at Johnson.

In space, Webb must be kept extremely cold in order to be able to detect the infrared light from very faint, distant objects. Webb and its instruments have an operating temperature of about 40 kelvin (about minus 387 degrees Fahrenheit / minus 233 degrees Celsius). Because the Webb telescope's mid-infrared instrument (MIRI) must be kept colder than the other research instruments, it relies on a cryocooler to lower its temperature to less than 7 kelvin (minus 447 degrees Fahrenheit / minus 266 degrees Celsius), another example of the technology that needed to be perfected to make Webb possible.

To protect the telescope from external sources of light and heat (like the Sun, Earth and Moon), as well as from heat emitted by the spacecraft, a five-layer, tennis court-sized sunshield acts like a parasol that provides shade. The sunshield separates the observatory into a warm, sun-facing side (reaching temperatures close to 185 degrees Fahrenheit / 85 degrees Celsius) and a cold side (minus 400 degrees Fahrenheit / minus 240 degrees Celsius). The sunshield blocks sunlight from interfering with the sensitive telescope instruments.

The next step toward completion for Webb's combined science instruments and optics is a trip to Northrop Grumman Aerospace Systems in Redondo Beach, California, where they will be integrated with the spacecraft element, which is the combined sunshield and spacecraft bus. Together, the pieces form the complete James Webb Space Telescope observatory.

All of the rigorous testing the telescope and the spacecraft have undergone to date show the mission is meeting its required performance levels. The sunshield and spacecraft bus experienced delays during their integration and testing at Northrop Grumman. Webb's spacecraft and sunshield are larger and more complex than most spacecraft. The combination of some integration activities taking longer than initially planned, such as the installation of more than 100 sunshield membrane release devices, has meant the integration and testing process is taking longer. Following a schedule assessment of the remaining integration and test activities, the Webb launch date was changed from October 2018 to between March and June 2019. Webb will launch from French Guiana on a European Space Agency-provided Ariane 5 launch vehicle. The existing program budget accommodates the change in launch date, and the change will not affect planned science observations.

WFIRST

After Webb, NASA's next great observatory will be WFIRST. The Wide Field Infrared Survey Telescope (WFIRST) was the top priority large-scale mission of the 2010 Decadal Survey for Astronomy and Astrophysics. Its purpose is to survey large swaths of sky to provide detailed information on the expansion history of the universe and conduct a large-scale search for extrasolar planets using gravitational lensing of the light of background stars. The project was initiated in 2016 and is in formulation, the earliest development phase.

WFIRST, in addition to studying dark energy, is being designed to carry a technology demonstration of a coronagraph instrument that will block the light of stars to let us directly image exoplanets and measure their light. The WFIRST coronagraph technology demonstration should be capable of seeing exoplanets that are up to one hundred million times fainter than their parent star. For the first time, we should able to measure the light directly from an exoplanet like Jupiter 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 an advanced coronagraph is coupled with a larger telescope.

In 2016, the National Academy of Sciences Midterm Assessment Report for the decadal survey affirmed WFIRST's scientific promise but cautioned against allowing the cost of the mission to affect the balance of missions and research in NASA's astronomy and astrophysics portfolio. The Midterm Assessment Report recommended that NASA commission an independent technical, management, and cost assessment of the project. That assessment, the WFIRST Independent External Technical/Management/Cost Review (WIETR), was conducted this year and concluded recently.

The WIETR found that the telescope's estimated life-cycle cost had increased since initiation due to expanded scope and requirements, a less-than-optimal funding profile, and a more mature understanding of the technical design. The NASA decision that initiated the WFIRST project set the project's budget at $3.2B (excluding Headquarters-held reserves), and the WIETR found that changes would eventually lead to a current project cost of $3.6B instead. I have directed the team to find reductions in scope and complexity sufficient to return the cost estimate to the $3.2B target set at project initiation and to report the results during a milestone review in February. At the same time, we are working with the project to establish a WFIRST management process consistent with the WIETR's findings, and we will provide a revised budget profile for the project. I look forward to seeing the redesigned WFIRST mission concept in February 2018 in advance of the April 2018 Key Decision Point at which the WFIRST cost will again be independently assessed.

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The next Decadal Survey

For over fifty 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, both for ground-based and space-based observatories. 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. The decadal surveys in astronomy and astrophysics do not focus exclusively on the largest missions, but highlight the need for a balanced program that has a mix of small, medium and large missions and activities. In addition, they provide the scientific community's assessment of the highest priority missions across all mission sizes, as well as the priorities for research and analysis, technology development, and maintaining the health of the field of astronomy and astrophysics.

As the time approaches to conduct the next Decadal Survey, we have initiated 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.

In support of these mission concept studies, the Astrophysics Division at NASA Headquarters is investing in the technologies necessary to make these missions feasible. The four teams have identified their critical technology gaps. Through its Strategic Astrophysics Technology program and its Supporting Research and Technology programs, NASA is investing in the maturation of mirror, detector, starshade, coronagraph, grating, cryocooler, and other technologies.

The Astrophysics Division has also commissioned studies of medium-sized mission concepts in preparation for the next decadal survey, a group of missions known as the Astrophysics Probes. These are missions sized between the large strategic observatories and the Astrophysics Explorers. Missions on this scale are focused on a specific scientific investigation. Previous missions of this scale are the Kepler and Fermi space telescopes.

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.

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A far-infrared surveyor might find biosignatures in the atmosphere of exoplanets (perhaps methane or ozone, 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.

Conclusion

As we close in on the sixtieth anniversary of the launch of Explorer 1 in January 2018, our understanding of the universe is much more comprehensive and multi-faceted, and scientifically much richer than it was when the earlier pioneers in space-based astrophysics were just getting started. Where we once may have wondered 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 and wonder what is happening on those worlds most like our own. Future astronomers have their work cut out for them with the missions under study and those that will be on orbit in the next few years.

I look forward to answering any questions you may have.

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

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

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

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

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

Chairman BABIN. Thank you very much, Dr. Zurbuchen. I now recognize Ms. Chaplain for five minutes to present her testimony.

TESTIMONY OF MS. CRISTINA CHAPLAIN, DIRECTOR, ACQUISITION AND SOURCING MANAGEMENT, U.S. GOVERNMENT ACCOUNTABILITY OFFICE

Ms. CHAPLAIN. Chairman Babin, Ranking Member Bera, Members of the Subcommittee, Chairman Smith and Ms. Chairman Johnson, thank you for inviting me today to discuss NASA's space telescopes. The focus of my statement will be on NASA's management of the three projects, TESS, WFIRST, and James Webb and what lessons we believe could benefit future NASA telescopes.

In total, the three telescopes represent an inspected investment of at least 12.4 billion and about 50 percent of the budget for astrophysics. As such, while it is important for NASA to stretch technological boundaries to further scientific research, it is also important to manage and oversee the projects prudently.

TESS is the smallest of the three projects at 336 million and closest to launch. It has not incurred costs or schedule delays at this point, though it has faced technical challenges. The projected launch date is currently March 2018. As it is in the final phases of development, TESS has been contending with an issue with camera performance and it faces the risk that its launch provider, SpaceX, may need more time than anticipated to be certified by NASA to fly. This is an upgraded version of the Falcon 9 launch vehicle, and it's the first time NASA is using it for science missions.

James Webb, as you know, is the largest and most complicated of the three programs and one of the most challenging NASA has ever undertaken. It's expected to cost $8.8 billion which is 78 percent more than anticipated when baselined. Since its rebaseline in 2011, James Webb has stayed within cost and schedule despite facing a myriad of technical, engineering, and manufacturing problems.

Healthy reserves have played an important role in keeping the program on track, but so have management and oversight practices which improved significantly after the rebaseline. The project is now in the midst of integration and testing, the most risky phase of its development. NASA recently announced a launch delay from October 2018 to the March through June timeframe of 2019. However, more delays are possible given the risks associated ahead, with the work ahead, and the level of schedule reserves that are now what is usually recommended, they're below what's recommended.

WFIRST is still in the early phases of the development process. It has not yet set baselines for cost and schedule but preliminary estimates have been ranging from $3.2 billion to $3.8 billion and preliminary launch dates range from 2024 to 2026. These estimates are under review as NASA responds to the independent review that found that mission scope is not aligned with resources provided.

All three telescope programs as well as many other NASA projects are heeding lessons from the past. For example, we've reported in recent years that NASA's made significant improvements to cost and schedule estimating and oversight processes. More projects are maturing critical technologies before they undertake full-scale acquisition activities. These and other actions have helped NASA to reduce cost and schedule growth over time.

As NASA assesses and undertakes future telescope efforts, there are four particular lessons learned that we believe should continue to be heeded. One is taking more steps or taking steps needed to ensure cost growth from a large project does not overwhelm the astrophysics portfolio. The recent WFIRST independent review was a good step in this direction as it took stock of a large project's business case before the most costly phases of acquisition begin.

Two, establish adequate cost and schedule reserves. The current set of telescope projects have generally benefitting from having robust reserves to address risk. But this is not the case across NASA. Notably, the human spaceflight projects have all been operating with very limited level of reserves. This has led them to defer work to address technical issues to stay within budget and put future cost reserves at risk of being overwhelmed by the deferred work.

Three, regularly update cost and schedule estimates. Programs have been reluctant to update joint confidence levels they establish at their baseline, and there's no requirement for them to do so. For James Webb, an updated estimate may have portended the current schedule delays.

Four, enhance oversight of contractors. Much has been done in recent years to better monitor contract performance, but we still find some projects that do not manage contractors well and react only after problems become overwhelming. A program on the scale of WFIRST or James Webb requires good lines of communication, rigorous monitoring of cost progress, insight into contract workforce levels, and having a government presence at contractor facilities among other actions.

This concludes my statement, and I'm happy to answer any questions you have.

[The prepared statement of Ms. Chaplain follows:]

United States Government Accountability Office

GAO

Testimony

Before the Subcommittee on Space, Committee on Science, Space, and Technology, House of Representatives

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NASA

Preliminary Observations on the Management of Space Telescopes

Statement of Cristina T. Chaplain, Director, Acquisition and Sourcing Management

GAO-18-277T

GAO Highlights

Highlights of GAO-18-277T, a testimony before the Subcommittee on Space, Committee on Science, Space, and Technology, House of Representatives

Why GAO Did This Study

Acquisition management has been a long-standing challenge at NASA, although GAO has reported on improvements the agency has made in recent years. Three space telescope projects are the key enablers for NASA to achieve its astrophysics' science goals, which include seeking to understand the universe. In its fiscal year 2018 budget request, NASA asked for about $697 million for these three projects, which represents over 50 percent of NASA's budget for its astrophysics' major projects. In total, these projects represent an expected investment of at least $12.4 billion.

This statement reflects preliminary observations on (1) the current status and cost of NASA's major telescope projects and (2) lessons learned that can be applied to NASA's management of its telescope projects. This statement is based on ongoing work on JWST and ongoing work on the status of NASA's major projects. Both reports are planned to be published in Spring 2018. This statement is also based on past GAO reports on JWST and NASA's acquisitions of major projects, and NASA input.

What GAO Recommends

GAO is not making any recommendations in this statement, but has made recommendations in prior reports to strengthen NASA's acquisition management of its major projects. NASA has generally agreed with GAO's recommendations and taken steps to implement them.

View GAO-18-277T. For more information, contact Cristina T. Chaplain at (202) 512-4841 or chaplainc@gao.gov.

December 6, 2017

NASA

Preliminary Observations on the Management of Space Telescopes

What GAO Found

The National Aeronautics and Space Administration's (NASA) current portfolio of major space telescopes includes three projects that vary in cost, complexity, and phase of the acquisition life cycle.

Table: Current Phase, Cost, and Schedule Status of National Aeronautics and Space Administration's (NASA) Major Space Telescope Projects

Project	Phase	Preliminary Cost Estimate (dollars in millions)		Preliminary Schedule	
Wide-Field Infrared Survey Telescope	Formulation (early phase)	3,200-3,800		2024-2026	
		Current Cost Estimate (dollars in millions)	**Change from Baseline (dollars in millions)**	**Target launch date**	**Change from baseline (months)**
Transiting Exoplanet Survey Satellite	Implementation (building, launching, and operating)	336.7	-41.7[a]	March 2018	-3
James Webb Space Telescope	Implementation (building, launching, and operating)	8,825.4	3,861.8	March-June 2019	57-60

Source: GAO analysis of National Aeronautics and Space Administration data. | GAO-18-277T

[a]The dollar change reflects a decrease of $26.7 million after launch vehicle selection in 2014 due to the reduction in planned costs and a decision by NASA in August 2017 to reallocate $15 million of the project's headquarters-held reserves to the Wide-Field Infrared Survey Telescope project.

GAO's ongoing work indicates that these projects are each making progress in line with their phase of the acquisition cycle but also face some challenges. For example, the current launch date for the James Webb Space Telescope (JWST) project reflects a 57-60-month delay from the project's original schedule. GAO's preliminary observations indicate this project still has significant integration and testing to complete, with very little schedule reserve remaining to account for delays. Therefore, additional delays beyond the delay of up to 8 months recently announced are likely, and funding available under the $8 billion Congressional cost cap for formulation and development may be inadequate.

There are a number of lessons learned from its acquisitions that NASA could consider to increase the likelihood of successful outcomes for its telescope projects, as well as for its larger portfolio of projects, such as its human spaceflight projects. For example, twice in the history of the JWST program, independent reviews found that the program was not holding adequate cost and schedule reserves. GAO has found that NASA has not applied this lesson learned to all of its large projects, and similar outcomes to JWST have started to emerge. For example, NASA did not incorporate this lesson with its human spaceflight programs. In July 2016 and April 2017, GAO found that these programs were holding inadequate levels of cost and schedule reserves to cover unexpected cost increases or delays. In April 2017, GAO recommended that NASA reassess the date of the programs' first test flight. NASA concurred and, in November 2017, announced a launch delay of up to 19 months.

Chairman Babin, Ranking Member Bera, and Members of the Subcommittee:

I am pleased to be here today to discuss the National Aeronautics and Space Administration's (NASA) management of its astrophysics' space telescope projects. These telescopes are the key enablers for the agency to achieve its astrophysics' science goals, which include seeking to understand the universe and our place in it. These major space telescope projects—projects with a life cycle cost greater than $250 million—include:

- the James Webb Space Telescope (JWST), which is designed to help understand the origin and destiny of the universe, the creation and evolution of the first stars and galaxies, and the formation of stars and planetary systems;
- the Transiting Exoplanet Survey Satellite (TESS), whose mission goal is to discover exoplanets—or planets in other solar systems—during transit, the time when the planet's orbit carries it in front of its star as viewed from Earth; and
- the Wide-Field Infrared Survey Telescope (WFIRST), which is designed to perform wide-field imaging and survey of the near-infrared sky to answer questions about the structure and evolution of the universe and expand our knowledge of planets beyond our solar system.

In its fiscal year 2018 budget request, NASA asked for about $697 million for these three projects, which represents over 50 percent of NASA's budget for its astrophysics' projects.[1] In total, these projects represent an expected investment of at least $12.4 billion. As such, while it is important for NASA to continually stretch technological boundaries to further scientific research, it is also important to manage these projects prudently, with clear accountability and oversight for taxpayer dollars.

For over two decades, acquisition management has been a long-standing challenge at NASA, although we have reported on improvements the agency has made in recent years.[2] We first designated NASA's

[1]According to NASA officials, NASA historically spends 50-70% of its astrophysics budget on developing new missions.

[2]For example, see GAO, *NASA: Assessments of Major Projects*, GAO-17-303SP (Washington, D.C.: May 16, 2017).

acquisition management as a high-risk area in 1990 in view of NASA's history of persistent cost growth and schedule slippage in the majority of its major systems. Our work has identified a number of causal factors related to these issues, including poor cost estimating and underestimation of risks associated with the development of its major systems. We have also identified a set of best practices that can help agencies manage development risks. NASA leadership has made concerted efforts to address these causal factors. In our February 2017 High Risk Update, however, we found that more needs to be done with respect to anticipating and mitigating risks—especially with regard to large programs, estimating and forecasting costs for its largest projects, and implementing management tools.[3]

My statement today provides our preliminary observations on (1) the current status and cost of NASA's major telescope projects and (2) lessons learned that can be applied to NASA's management of its telescope projects. This statement is based on our ongoing work for this committee and others on the JWST project and our annual review of the status of all of NASA's major projects, as well as our February 2017 High-Risk Update and other past reports.[4] To assess the cost and schedule performance of these projects, we collected information on these areas from projects using a data collection instrument, analyzed projects' monthly status reports, interviewed NASA project and headquarters officials, and reviewed project documentation. For JWST and TESS, which are in the implementation phase, we compared current cost and schedule estimates to their original cost and schedule baselines. To identify lessons learned that can be applied to NASA's management of its telescope projects, we examined NASA's efforts to address issues identified in our prior JWST work, such as the quality of the cost and schedule risk analyses, and our February 2017 High-Risk Update.[5]

[3]GAO, *High-Risk Series: Progress on Many High-Risk Areas, While Substantial Efforts Needed on Others*, GAO-17-317 (Washington, D.C.: Feb. 15, 2017).

[4]GAO, *James Webb Space Telescope: Actions Needed to Improve Cost Estimate and Oversight of Test and Integration*, GAO-13-4 (Washington, D.C.: Dec. 3, 2012); GAO, *NASA: Assessments of Selected Large-Scale Projects*, GAO-13-276SP (Washington, D.C.: Apr. 17, 2013); GAO, *James Webb Space Telescope: Project Meeting Commitments but Current Technical, Cost, and Schedule Challenges Could Affect Continued Progress*, GAO-14-72 (Washington, D.C.: Jan. 8, 2014); GAO, *NASA: Assessments of Major Projects*, GAO-16-309SP (Washington, D.C.: Mar. 30, 2016); GAO-17-303SP; and GAO-17-317.

[5]GAO-13-4, GAO-13-276SP, GAO-14-72, and GAO-17-303SP.

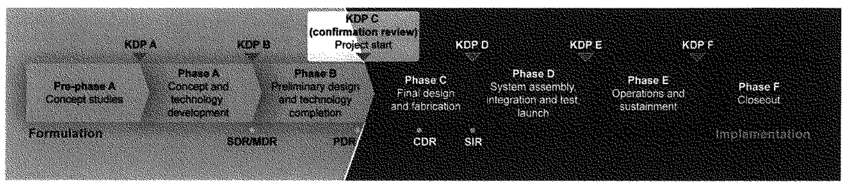
We are conducting the work on which this statement is based in accordance with generally accepted government auditing standards. We plan to issue a final report on our annual review of the JWST program, as well as our annual assessment of NASA's major projects, in Spring 2018. NASA provided us technical comments on information that is included in this statement on the telescope projects, which we incorporated as appropriate.

Background

NASA's mission is to drive advances in science, technology, aeronautics, and space exploration, and contribute to education, innovation, our country's economic vitality, and the stewardship of the Earth. To accomplish this mission, NASA establishes programs and projects that rely on complex instruments and spacecraft. NASA's portfolio of major projects ranges from space satellites equipped with advanced sensors to study the Earth to a telescope intended to explore the universe to spacecraft to transport humans and cargo to and beyond low-Earth orbit. Some of NASA's projects are expected to incorporate new and sophisticated technologies that must operate in harsh, distant environments.

The life cycle for NASA space flight projects consists of two phases—formulation, which takes a project from concept to preliminary design, and implementation, which includes building, launching, and operating the system, among other activities. NASA further divides formulation and implementation into phase A through phase F. Major projects must get approval from senior NASA officials at key decision points before they can enter each new phase. Figure 1 depicts NASA's life cycle for space flight projects.

Figure 1: NASA's Life Cycle for Space Flight Projects



Management decision reviews

KDP = key decision point

Technical reviews

SDR/MDR = system definition review/mission definition review

PDR = preliminary design review

CDR = critical design review

SIR = system integration review

Source: NASA data and GAO analysis. | GAO-18-277T

Formulation culminates in a review at key decision point C, known as project confirmation, where cost and schedule baselines are established and documented in a decision memorandum. To inform those baselines, each project with a life-cycle cost estimated to be greater than $250 million must also develop a joint cost and schedule confidence level (JCL). The JCL initiative, adopted in January 2009, is a point-in-time estimate that, among other things, includes all cost and schedule elements, incorporates and quantifies known risks, assesses the impacts of cost and schedule to date, and addresses available annual resources. NASA policy requires that projects be baselined and budgeted at the 70 percent confidence level.[6]

The agency baseline commitment established at key decision point C includes cost and schedule reserves held at the project—those within the project manager's control—and NASA headquarters level.[7] Cost reserves

[6]NASA Procedural Requirements 7120.5E NASA Space Flight Program and Project Management Requirements para 2.4.4 (Aug. 14, 2012) (hereinafter cited as NPR 7120.5E (Aug. 14, 2012). The decision authority for a project can approve it to move forward at less than the 70 percent confidence level. That decision must be justified and documented.

[7]NASA refers to cost reserves as unallocated future expenses.

are for costs that are expected to be incurred—for instance, to address project risks—but are not yet allocated to a specific part of the project. Schedule reserves are extra time in project schedules that can be allocated to specific activities, elements, and major subsystems to mitigate delays or address unforeseen risks.

Status of NASA's Major Telescope Projects

NASA's current portfolio of major space telescopes includes three projects—WFIRST, TESS, and JWST—that vary in cost, complexity, and phase of the acquisition life cycle. WFIRST, a project that entered the concept and technology development phase and established preliminary cost and schedule estimates in February 2016, is in the earliest stages of the acquisition life cycle. With preliminary cost estimates ranging from $3.2 billion to $3.8 billion, this project is an observatory designed to perform wide-field imaging and survey of the sky at near-infrared wavelengths to answer questions about the structure and evolution of the universe and to expand our knowledge of planets beyond our solar system. The current design includes a 2.4 meter telescope that was built and qualified for another federal agency over 10 years ago; the project is evaluating which components to reuse and which to modify, refurbish, or build new. TESS—a smaller project whose latest cost estimate is approximately $337 million—is targeted to launch in March 2018 and will be used to conduct the first extensive survey of the sky from space for transiting exoplanets.

And finally, JWST, with a life-cycle cost estimate of $8.835 billion, is one of NASA's most complex projects and top priorities. The telescope is designed to help understand the origin and destiny of the universe, the creation and evolution of the first stars and galaxies, and the formation of stars and planetary systems. With a 6.5-meter primary mirror, JWST is expected to operate at about 100 times the sensitivity of the Hubble Space Telescope. JWST's science instruments are to detect very faint infrared sources and, as such, are required to operate at extremely cold temperatures. To help keep these instruments cold, a multi-layered tennis-court-sized sunshield is being developed to protect the mirrors and instruments from the sun's heat.

We have reported for several years on the JWST project, which has experienced significant cost increases and schedule delays. Prior to being approved for development, cost estimates for JWST ranged from $1 billion to $3.5 billion, with expected launch dates ranging from 2007 to 2011. Before 2011, early technical and management challenges, contractor performance issues, low levels of cost reserves, and poorly phased funding levels caused JWST to delay work after confirmation, which contributed to significant cost and schedule overruns, including launch delays. The Chair of the Senate Subcommittee on Commerce, Justice, Science, and Related Agencies requested from NASA an independent review of JWST in June 2010. In response, NASA commissioned the Independent Comprehensive Review Panel, which issued its report in October 2010. The panel concluded that JWST was executing well from a technical standpoint, but that the baseline cost estimate did not reflect the most probable cost with adequate reserves in each year of project execution, resulting in an unexecutable project.[8]

Following this review, Congress in November 2011 placed an $8 billion cap on the formulation and development costs for the project and NASA rebaselined JWST with a life-cycle cost estimate of $8.835 billion that included additional money for operations and a planned launch in October 2018.[9] The new baseline represented a 78 percent increase to the project's life-cycle cost from the original baseline and a launch date in October 2018, a delay of 52 months. The revised life-cycle cost estimate included a total of 13 months of funded schedule reserve.[10]

Our ongoing work indicates that these three projects are each making progress in line with their phase of the acquisition cycle, but also face challenges in execution. Some of these challenges are unique to the projects themselves and some are common among the projects in NASA's portfolio. For example, when projects enter the integration and test phase, unforeseen challenges can arise and affect the cost and schedule for the project. Table 1 provides more details about the current acquisition phase, cost, and schedule status of NASA's major space telescope projects based on our ongoing work.

[8]James Webb Space Telescope (JWST) Independent Comprehensive Review Panel (ICRP): Final Report (Oct. 29, 2010).

[9]A rebaseline is a process initiated if development cost growth is more than 30 percent. This process requires the NASA Administrator to transmit a report to the Committee on Science, Space, and Technology of the House of Representatives and the Committee on Commerce, Science, and Transportation of the U.S. Senate. In addition, if a project or program milestone is likely to be delayed by 6 months or more, a report to the committees is required.

[10]The 2011 rebaseline had 13 months of schedule reserve. However, by accelerating some work, the project was able to increase the schedule reserve to 14 months in June 2012.

Table 1: Current Phase, Cost, and Schedule Status of National Aeronautics and Space Administration's (NASA) Major Space Telescope Projects

Project	Acquisition Phase	Life-Cycle Cost Estimate			Schedule		
		Preliminary Cost (then-year dollars in millions)			Preliminary Schedule		
Wide-Field Infrared Survey Telescope (WFIRST)	Concept and technology development	3,200-3,800			2024-2026		
		Baseline (then-year dollars in millions)	Latest Estimate (then-year dollars in millions)	Dollar Change (in millions)	Baseline	Target Date	Change (months)
Transiting Exoplanet Survey Satellite (TESS)	System assembly, integration and test, and launch	378.4	336.7	-41.7[a]	June 2018	March 2018	-3
James Webb Space Telescope (JWST)	System assembly, integration and test, and launch	4,963.6	8,825.4	3,861.8	June 2014	March-June 2019	57-60

Source: GAO analysis of National Aeronautics and Space Administration data. | GAO-18-277T

[a]NASA decreased TESS's life-cycle cost by $26.7 million after launch vehicle selection in 2014 due to the reduction in planned costs. At its most recent key decision review in August 2017, NASA decreased the project's life-cycle costs again by reallocating $15 million of TESS's headquarters-held reserves to the WFIRST project.

WFIRST. NASA's preliminary cost and schedule estimates for the WFIRST project are currently under review as the project responds to findings in the WFIRST Independent External Technical/Management/Cost Review. This independent review was conducted to ensure the mission's scope and required resources are well understood and executable. NASA initiated this review in April 2017 to address the National Academies' concerns that WFIRST cost growth could endanger the balance of NASA's astrophysics program and negatively affect other scientific priorities. The review found that the mission scope is understood, but not aligned with the resources provided and concluded that the mission is not executable without adjustments and/or additional resources. For example, the study team found that NASA's current forecasted funding profile for the WFIRST project would require the project to slow down activities starting in fiscal year 2020, which would result in an increase in development cost and schedule. NASA agreed with the study team's results and directed the project to reduce the cost and complexity of the design in order to maintain costs within the $3.2 billion cost target.

The project is currently identifying potential ways to reduce the scope of planned activities (called "descopes"), assessing the science impact of those descopes, and then developing recommendations for the Astrophysics Division leadership. An example of a descope that may be considered is the requirement for WFIRST to be "star-shade ready," which means the design must be compatible with a star-shade device that is positioned between it and the star being observed to block out starlight while allowing the light emitted by the planet through.

TESS. The TESS project is currently holding cost and schedule reserves consistent with NASA center requirements, but there are no longer headquarters-held cost reserves to cover a delay if the project cannot launch as planned in March 2018.[11] According to a project official, the project is holding 16 days of schedule reserve to its target March 2018 launch readiness date, which includes 6 days for the completion of integration and test, and 10 days for launch operations. The project previously used schedule reserves to accommodate the delayed delivery of its Ka-band transmitter, which is essential for TESS as it transmits the mission data back to Earth, due to continued performance and manufacturing issues. The two main risks to the March 2018 launch date are if: 1) SpaceX requires additional time past December 2017 for NASA's Launch Services Program to certify that TESS can fly on its upgraded launch vehicle—certification is necessary because it will be the first time that NASA will use this version of the vehicle—and 2) any issues are identified during the remainder of environmental testing.

The project is also conducting additional testing on its spare camera at temperatures seen in space to better understand expected camera performance on orbit. TESS will use four identical, wide field-of-view cameras to conduct the first extensive survey of the sky from space for transiting exoplanets. However, during thermal testing, the project found that the substance attaching the lenses to the camera barrel places pressure on the lenses and causes the cameras to be slightly out of focus. In June 2017, NASA directed the project to proceed with integrating the cameras—as they are expected to meet TESS's top level science requirements even with the anomaly. At its most recent key

[11]Both NASA headquarters and the project hold cost reserves for projects. Project-held cost reserves are within the project manager's control. NASA headquarters may allocate cost reserves to the project when project-held cost reserves are not enough to cover additional time and money needed to complete a project or there is an issue outside of the project's control.

decision review in August 2017, NASA reallocated $15 million of TESS's headquarters-held reserves to the WFIRST project. While this had the effect of decreasing life cycle costs for TESS, it also increased risk as the project no longer has any additional headquarters-held cost reserves to cover a launch delay past March 2018.

JWST. The JWST project continues to make progress towards launch, but the program is encountering technical challenges that require both time and money to fix and may lead to additional delays, beyond a delay recently announced. While the project has made much progress on hardware integration and testing over the past several months, it also used all of its remaining schedule reserves to address various technical issues, particularly on the spacecraft element. In September 2017, the JWST project requested from the European Space Agency—who will contribute the Ariane V launch vehicle—a launch window from March to June 2019, or 5 to 8 months later than the planned October 2018 launch readiness date, established in 2011. The project based this request on the results of a schedule risk assessment that incorporated inputs from the contractor on expected durations of ongoing spacecraft element integration work and other challenges that were expected to increase schedule.

With the later launch window to June 2019, the project expected to have up to 4 months of new schedule reserves. However, shortly after requesting the revised launch window, the project learned from its contractor that up to another 3 months of schedule reserve use is likely, due to lessons learned from conducting deployment exercises of the sunshield, such as reach and access limitations on the flight hardware. As a result, and pending further examination of the schedule, the project now has approximately one month of schedule reserve to complete environmental testing of the spacecraft element and the final integration phase. The final integration phase is where the instruments and telescope will be integrated with the spacecraft and sunshield to form the completed observatory. As I previously noted, our work has shown the integration and test is the riskiest phase of development, where problems are most likely to be found and schedules slip. Given the risks associated with the integration and test work ahead, coupled with a level of schedule reserves that is currently well below the level stated in the procedural requirements issued by the NASA center responsible for managing JWST, additional delays to the project's revised launch readiness date of

June 2019 are likely.[12] As a result, the funding available under the Congressional cost cap of $8 billion may be inadequate as the contractor will need to continue to retain higher workforce levels for longer than expected to prepare the mission for a delayed launch.

Lessons Learned from NASA Acquisitions

As Congress, NASA, and the science community consider future telescope efforts, it will be exceedingly important to shape and manage new programs in a manner that minimizes cost overruns and schedule delays. This is particularly important for the largest programs as even small cost increases can have reverberating effects. NASA's telescope and other science projects will always have inherent technical, design, and integration risks because they are complex, specialized, and often push the state of the art in space technology. But too often, our reports find that management and oversight problems—which can include poor planning, optimistic cost estimating, funding gaps, lax oversight, and poor contractor performance, among other issues—are the real drivers behind cost and schedule growth.

To its credit, NASA has taken significant steps, partly in response to our past recommendations, to reduce acquisition risk from both a technical and management standpoint, including actions to enhance cost and schedule estimating, provide adequate levels of reserves to projects, establish better processes and metrics to monitor projects, and expand the use of earned value management to better monitor contractor performance. For example, in November 2012, we found that NASA employee skill sets available to analyze and implement earned value management vary widely from center to center, and we recommended that NASA conduct an earned value management skills gap analysis to identify areas requiring augmented capability across the agency, and, based on the results of the assessment, develop a workforce training plan to address any deficiencies.[13] NASA concurred with this recommendation and developed an earned value management training plan in 2014 based on the results of an earned value management skills gap analysis that

[12]NASA's Goddard Space Flight Center is the NASA center with responsibility for managing JWST and has issued procedural requirements that establish the levels of both cost and schedule reserves that projects must hold at various points in the project life cycle. Goddard Space Flight Center, Goddard Procedural Requirements 7120.7, Schedule and Budget Margins for Flight Projects (Feb 28, 2017).

[13]GAO, *NASA: Earned Value Management Implementation across Major Spaceflight Projects Is Uneven*, GAO-13-22 (Washington, D.C.: Nov. 19, 2012).

was conducted in 2013. Moreover, in recent years, we have found that many of the projects within the agency's major project portfolio have improved their cost and schedule performance.[14] Nevertheless, the extent to which NASA has adopted some of the following lessons learned within its portfolio of major projects is mixed, and NASA has an opportunity to strengthen its program management of major acquisitions, including its space telescopes, by doing so.

Manage Cost and Schedule Performance for Large Projects to Limit Implications for Entire Portfolio. In 2013, following JWST's cost increases and schedule growth, we found that though cost and schedule growth can occur on any project, increases associated with NASA's most costly and complex missions can have cascading effects on the rest of the portfolio.[15] For example, we found that the JWST cost growth would have reverberating effects on the portfolio for years to come and required the agency to identify $1.4 billion in additional resources over fiscal years 2012 through 2017, according to Science Mission Directorate officials. NASA identified approximately half of this required funding from the four science divisions within the Science Mission Directorate account. The majority of the cuts were related to future high priority missions, missions in the operations and sustainment phase, and research and analysis.

In essence, NASA had to mortgage future high priority missions and research to address JWST's additional resource needs. Similarly, the National Academy of Sciences has concluded in the past that it is important for NASA to have a clearly articulated and consistently applied method for prioritizing why and how its scarce fiscal resources are apportioned with respect to the science program in general and on a more granular level among component scientific disciplines. The academy noted that failure to do so could result in a loss of capacity, capability, and human resources in a number of scientific disciplines and technological areas that may take a generation or more to reconstitute once eliminated.[16] NASA's establishment of the WFIRST Independent External Technical/Management/Cost Review that I previously discussed is a step in the right direction to help ensure the Astrophysics Division incorporates this lesson learned.

[14]GAO-16-309SP and GAO-17-303SP.

[15]GAO-13-276SP.

[16]The National Academy of Sciences, *Review of the Draft 2014 Science Mission Directorate Science Plan* (Washington, D.C.: National Academies Press, 2013).

Establish Adequate Cost and Schedule Reserves to Address Risks. Twice in the history of the JWST program, independent reviewers found that the program's planned cost reserves were inadequate. First, in April 2006, an Independent Review Team confirmed that the project's technical content was complete and sound, but expressed concern over the project's reserve funding, reporting that it was too low and phased in too late in the development lifecycle. The review team reported that for a project as complex as JWST, 25 to 30 percent total reserve funding was appropriate. The team cautioned that low reserve funding compromised the project's ability to resolve issues, address risk areas, and accommodate unknown problems. As I previously mentioned, following additional cost increases and schedule threats, NASA commissioned the Independent Comprehensive Review Panel. In 2010, the panel again concluded JWST was executing well from a technical standpoint, but that the baseline cost estimate did not reflect the most probable cost with adequate reserves in each year of project execution, resulting in an unexecutable project.[17]

NASA heeded these lessons when it established a new baseline for JWST in 2011. For example, the revised schedule included more reserves than required by the procedural requirements issued by the NASA center responsible for managing JWST. We have found, however, that NASA has not applied this lesson learned to all of its large projects—most notably with its human spaceflight projects, including the Space Launch System, Orion Crew Capsule, and associated ground systems—and similar outcomes to the JWST project have started to emerge with these projects. We previously reported that all three of these programs were operating with limited cost reserves, which limited each program's ability to address risks and unforeseen technical challenges.

For example, we found in July 2016 that the Orion program planned to maintain very low levels of annual cost reserves until 2018.[18] The lack of available cost reserves in the near term led to the program deferring work to address technical issues to stay within budget, and put the program's future cost reserves at risk of being overwhelmed by deferred work. In April 2017, we also found that all three programs faced development

[17]James Webb Space Telescope (JWST) Independent Comprehensive Review Panel (ICRP): Final Report (Oct. 29, 2010).

[18]GAO, *Orion Multi-Purpose Crew Vehicle: Action Needed to Improve Visibility into Cost, Schedule, and Capacity to Resolve Technical Challenges*, GAO-16-620 (Washington, D.C.: July 27, 2016).

challenges in completing work, and each had little to no schedule reserve remaining to the launch date—meaning they would have to complete all remaining work with minimal delay during the most challenging stage of development.[19] We found that it was unlikely that the programs would achieve the planned launch readiness date and recommended that NASA reassess the date. NASA agreed with this recommendation and stated that it would establish a new launch readiness date. In November 2017, NASA announced that a review of the possible manufacturing and production schedule risks indicated a launch date of June 2020—a delay of 19 months—but the agency will manage to a December 2019 launch date because, according to NASA, they have put in mitigation strategies for those risks. We will follow-up on those mitigation strategies as part of future work on the human space exploration programs.

Regularly and Consistently Update Project JCLs to Provide Realistic Estimates to Decision Makers. In 2009, NASA began requiring that programs and projects with estimated life-cycle costs greater than $250 million develop a JCL prior to project confirmation. This was a positive step for NASA to help ensure that cost and schedule estimates are realistic and projects are thoroughly planning for anticipated risks. This is because a JCL assigns a confidence level, or likelihood, of a project meeting its cost and schedule estimates. Our cost estimating best practices recommend that cost estimates should be updated to reflect changes to a program or be kept current as a program moves through milestones.[20] As new risks emerge on a project, an updated cost and schedule risk analysis can provide realistic estimates to decision-makers, including the Congress. This is especially true for NASA's largest projects as updated estimates may require the Congress to consider a variety of actions.

However, there is no requirement for NASA projects to update their JCLs, and our prior work has found that projects—including JWST—do not regularly update cost risk analyses to take into account newly emerged risks.[21] Our ongoing work indicates that of the 16 major projects currently

[19]GAO, *NASA Human Space Exploration: Delay Likely for First Exploration Mission*, GAO-17-414 (Washington, D.C.: Apr. 27, 2017).

[20]GAO, *GAO Cost Estimating and Assessment Guide: Best Practices for Developing and Managing Capital Program Costs,* GAO-09-3SP (Washington, D.C.: Mar. 2, 2009).

[21]GAO-13-4 and *Space Launch System: Management Tools Should Better Track Cost and Schedule Commitments to Adequately Monitor Increasing Risk,* GAO-15-596 (Washington, D.C.: Jul. 16, 2015).

in NASA's portfolio that have developed JCL estimates, only 2 have reported updating their JCLs (other than required due to a rebaseline). For example, the Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport Project (InSight), a Mars lander, updated its JCL after the project missed its committed launch date. As a result, the project was able to provide additional information to decision makers about the probability that it will meet its revised cost and schedule estimates. As a project reaches the later stages of development, especially integration and testing, the types of risks the project will face may change. An updated project JCL would provide both project and agency management with data on relevant risks that can guide the project decisions. For example, in December 2012, we recommended the JWST project update its JCL.[22] NASA concurred with this recommendation; however, we recently closed the recommendation because NASA had not taken steps to implement it and the amount of time remaining before launch would not have allowed the benefit of implementing the recommendation to be realized. An updated JCL may have portended the current schedule delays, which could have been proactively addressed by the project.

Enhance Oversight of Contractors to Improve Project Outcomes. In December 2012, we found that the JWST project had taken steps to enhance communications with and oversight of its contractors.[23] According to project officials, the increased communication allowed them to better identify and manage project risks by having more visibility into contractors' activities. The project reported that a great deal of communication existed across the project prior to the Independent Comprehensive Review Panel; however, additional improvements were made. For example, the project increased its presence at contractor facilities as necessary to provide assistance; this included assigning two engineers on a recurring basis at a Lockheed Martin facility to assist in solving problems with an instrument. The JWST project also assumed full responsibility for the mission system engineering functions from Northrop Grumman in March 2011. NASA and Northrop Grumman officials both said that NASA is better suited to perform these tasks.

We continue to see instances in our ongoing work that highlight the importance of implementing this lesson learned from JWST. For example,

[22]GAO-13-4.

[23]GAO-13-4.

we found in 2017 that the Space Network Ground Segment Sustainment project—a project that plans to develop and deliver a new ground system for one Space Network site that provides essential communications tracking services to NASA and non-NASA missions—exceeded its original cost baseline by at least $401.7 million and been delayed by 27 months.[24] The project has attributed some of the cost overruns and schedule delays to the contractor's incomplete understanding of its requirements, which led to poor contractor plans and late design changes. The project also took steps to assign a new NASA project manager, increase physical presence at the contractor facility, and have more staff focused on validation and verification activities.

In summary, NASA continues to make progress developing its space telescopes to help understand the universe and our place in it. But much like other major projects that NASA is developing, there continues to be an opportunity for NASA to learn from JWST and other projects that have suffered from cost overruns and schedule delays. Key project management tools and prior GAO recommendations that I have highlighted here today, could help to better position these large, complex, and technically challenging efforts for a successful outcome. We look forward to continuing to work with NASA and this subcommittee in addressing these issues.

Chairman Babin, Ranking Member Bera, and Members of the Subcommittee, this completes my prepared statement. I would be pleased to respond to any questions that you may have at this time.

[24]GAO-17-303SP. In 2016, NASA announced it was reclassifying SGSS as a hybrid sustainment project for the Space Network. A hybrid sustainment effort is a sustainment effort that still includes development work. The SGSS project expects to experience additional cost growth and schedule delays, but the exact magnitude is unknown. The project was reevaluating its cost and schedules at the time of the review.

GAO Contact and Staff Acknowledgments

If you or your staff have any questions about this testimony, please contact Cristina T. Chaplain, Director, Acquisition and Sourcing Management at (202) 512-4841 or chaplainc@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this statement. GAO staff who made key contributions to this statement include Molly Traci, Assistant Director; Richard Cederholm, Assistant Director; Carrie Rogers; Lisa Fisher; Laura Greifner; Erin Kennedy; and Jose Ramos.

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Cristina T. Chaplain

Ms. Chaplain currently serves as a Director, Acquisition and Sourcing Management, at the U.S. Government Accountability Office. She has responsibility for GAO assessments of military space acquisitions, NASA, and the Missile Defense Agency. Among other topics, she has led reviews on the International Space Station, the Space Launch System and the Orion crew capsule, acquisition progress for major NASA projects, the James Webb telescope, commercial cargo and crew, NASA contract management, contract terminations, weather satellites, and the Global Positioning System. In addition to her work on space and missile system development, Ms. Chaplain has led a variety of DOD-wide contracting-related and best practice evaluations for the GAO. Before her current position, Ms. Chaplain worked with GAO's financial management and information technology teams. Ms. Chaplain has been with the GAO for 26 years. She received a bachelor's degree, magna cum laude, in International Relations from Boston University and a Masters Degree in Journalism from Columbia University.

Chairman BABIN. Thank you very much. I now recognize Mr. Young for five minutes to present his testimony.

TESTIMONY OF MR. A. THOMAS YOUNG, FORMER DIRECTOR, GODDARD SPACE FLIGHT CENTER, NASA; FORMER PRESIDENT AND CHIEF OPERATING OFFICER, MARTIN MARIETTA CORPORATION

Mr. YOUNG. Space telescopes are a valuable and mandatory asset in the scientific exploration of our solar system, our galaxy, and the universe. Space telescopes range in size from explorers to large flagship missions. The 2010 Decadal survey emphasized the importance of maintaining a balance in the mix of explorers and large missions.

Flagship missions such as Hubble, James Webb Space Telescope and WFIRST are mandatory to pursue scientific priorities that can only be investigated with large systems. NASA's Explorer Program has a rich history of scientific discovery and provides critical opportunities to develop scientists and engineers for the future.

The excellence of the United States' Astronomy and Astrophysics Program cannot be maintained without a healthy balance of large, medium and small missions.

I shall concentrate my comments upon JWST and WFIRST. These two flagship missions are in very different phases of their development with very different current challenges. Each mission requires bold leadership to assure mission success.

JWST was the highest ranked mission in the 2001 Decadal survey. Clearly, JWST is one of the most important and challenging civil space missions ever undertaken. JWST has a history of cost growth and schedule delays. It also has a history of development success on a project with significant technological challenges.

NASA made a decision a few years ago to fix JWST programmatic issues by budgeting to the most probable cost and scheduling to the most probable schedule. Until recently, performance to this revised plan has been quite good. The current assessment of JWST's status is that integration and test will take significantly longer than planned. The result is a launch schedule delay and the consumption of most of the remaining funding resources. In my opinion, the launch date and required funding cannot be determined until a new plan is thoroughly developed and verified by independent review.

The bold leadership I spoke of earlier is required to assure that risk is not added to the program while trying to minimize the schedule and cost impacts. JWST is at a point in this development where the only criterion that is important is mission success. Every appropriate thing that can be done to maximize the probability of success should be done. At this stage of the project, a few extra days or weeks or even months of schedule delay or the expenditure of some additional dollars is a small price to pay to assure success of a mission as important as JWST.

Turning to WFIRST, it was the top priority mission in the 2010 Decadal survey. It was defined as a significant scientific mission with medium cost and risk. However, WFIRST has had requirements creep to the degree that medium cost and risk no longer applies. Each of the added requirements has contributed to the scientific value of the mission, but at a cost. The cost is additional risk, cost, and a potential erosion of program balance that was so strongly emphasized in the 2010 Decadal survey.

The bold leadership I spoke of earlier is required to assure that the most comprehensive and scientifically valuable Astronomy and Astrophysics Program, including WFIRST, is implemented. As the Decadal survey's highest priority, WFIRST must be successfully completed. The good news is that WFIRST has not yet reached Milestone B. All requirements are currently controllable. NASA is to be congratulated for taking an important step with the establishment of the WFIRST Independent External Technical/Management/Cost Review. This review has effectively defined the scope, cost, and risk issues for WFIRST. The next step is to decide the scope, cost, and risk appropriate for a top priority flagship mission that is consistent with a balanced Astronomy and Astrophysics Program.

I want to emphasize that there is no cause for panic. What is transpiring is a perfectly healthy process to assure that the scope, cost, and risk are appropriately defined prior to proceeding past Milestone B.

Many studies have shown that the two most significant causes of cost growth and schedule erosion are failure to budget to the most probable cost and failure to control requirements. The history of JWST has been plagued with the failure to budget to the most probable cost. This problem has been true for many space programs. NASA has largely corrected this problem by implementing a policy that requires statistical and independent cost estimating and budgeting to the most probable cost which NASA has defined as 70/30.

WFIRST has been plagued with continual requirements creep. The implementation of a comprehensive, independent requirements review prior to Milestone B, followed by a rigorous decision process, will mitigate this issue. The process being implemented for WFIRST should become standard for all major NASA projects.

I believe NASA has the ability to manage large space telescope projects. Implementing statistical and independent cost estimating followed by budgeting to the most probable cost is a major improvement. Prior to Milestone B, conducting an independent, external review of requirements, cost and risk that is followed by a decision process that assures the mission is consistent with the Decadal survey including a balanced scientific program is equally important. Following Milestone B, requirements must be rigorously managed to prevent requirements creep.

Thank you.

[The prepared statement of Mr. Young follows:]

TESTIMONY TO THE COMMITTEE

ON

SCIENCE, SPACE AND TECHNOLOGY

SUBCOMMITTEE ON SPACE

DECEMBER 6, 2017

A. THOMAS YOUNG

Chairman Babin, Ranking Member Bera and Committee members, I am pleased to present my views on the management of large space telescope projects.

Space telescopes are a valuable and mandatory asset in the scientific exploration of our solar system, our galaxy and the universe. Space telescopes range in size from Explorers to large flagship missions. The 2010 Decadal Survey emphasized the importance of maintaining a balance in the mix of Explorers and large missions. Flagship missions such as Hubble, James Webb Space Telescope (JWST) and WFIRST are mandatory to pursue scientific priorities that can only be investigated with large systems. NASA's Explorer Program has a rich history of scientific discovery and provides critical opportunities to develop scientists and engineers for the future. The excellence of the U. S. Astronomy and Astrophysics Program cannot be maintained without a healthy balance of large, medium and small missions.

I shall concentrate my comments upon JWST and WFIRST. These two flagship missions are in very different phases of their development with very different current challenges. Each mission requires bold leadership to assure mission success.

JWST was the highest ranked mission in the 2001 Decadal Survey. Clearly, JWST is one of the most important and challenging civil space missions ever undertaken. JWST has a history of cost growth and schedule delays. It also has had a history of development success on a project with significant technological challenges. NASA made a decision a few years ago to "fix" JWST programmatic issues by budgeting to the most probable cost and scheduling to the most probable schedule. Until recently, performance to this revised plan has been quite good. The current assessment of JWST's status is that integration and test will take significantly longer than planned. The result is a launch schedule delay and the consumption of most of the remaining funding reserves. In my opinion, the launch date and required funding cannot be determined until a new plan is thoughtfully developed and verified by independent review.

The bold leadership I spoke of earlier is required to assure that risk is not added to the program while trying to minimize the schedule and cost impacts. JWST is at the point in its development where the only criterion that is important is mission success. Every appropriate thing that can be done to maximize the probability of success should be done. At this stage of the project, a few extra days or weeks or even months of schedule delay or the expenditure of some additional dollars is a small price to pay to assure success of a mission as important as JWST.

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Thank you, I will be pleased to respond to any questions you may have.

A. Thomas Young

A. Thomas Young is the former Director of NASA's Goddard Space Flight Center, President and COO of Martin Marietta and Chairman of SAIC. He retired from Lockheed Martin in July, 1995 and the SAIC Board in 2013. Mr. Young is involved in various advisory and review activities associated with the U.S. Space Program.

Mr. Young began his career with NASA at the Langley Research Center in 1961. He was a member of the Lunar Orbiter Project Team and was Mission Director for Project Viking, which resulted in the successful landing of two spacecraft on the surface of Mars. He became Director of the Planetary Program at NASA Headquarters in 1976 and was appointed Deputy Director of the Ames Research Center in 1978. Mr. Young was Director of the Goddard Space Flight Center from 1979 to 1982. He joined the Martin Marietta Corporation in 1982 and was subsequently President of Baltimore Aerospace and the Electronics and Missiles Group. Mr. Young was President and COO of Martin Marietta from 1990 to 1995.

Mr. Young is a Honorary Fellow of the American Institute of Aeronautics and Astronautics, a Fellow of the American Astronautical Society, a Fellow of the Royal Astronautical Society and a Fellow of the International Academy of Astronautics. He is a member of the National Academy of Engineering and the University of Virginia Raven Society. Mr. Young is a former member of the NASA Advisory Council.

Mr. Young earned a bachelor of aeronautical engineering degree and a bachelor of mechanical engineering degree in 1961 from the University of Virginia. In 1972 he received a masters of management degree from MIT which he attended as a Sloan Fellow. He also holds a honorary doctor of science degree from Salisbury University.

Chairman BABIN. Thank you, Mr. Young. I appreciate your testimony. I now recognize Dr. Mountain for five minutes to present your testimony.

TESTIMONY OF DR. MATT MOUNTAIN, PRESIDENT, ASSOCIATION OF UNIVERSITIES FOR RESEARCH IN ASTRONOMY

Dr. MOUNTAIN. Mr. Chairman and Members of the Subcommittee, Chairman Smith, thank you for the opportunity to testify.

These are exciting times. The progress of science and technology that's been under the purview of this Subcommittee and the Science Committee overall has been quite transformative.

We now have the potential, for the first time in human history, to answer a profound question that's haunted us for millennia: Are we alone in the universe? We are at a unique point in our history.

As we've heard from Dr. Zurbuchen, we know almost every star we can see has a planetary system. We heard from Chairman Babin what incredible things happened down at the Johnson Space Center where, through a hurricane, we showed the largest space telescope mirror ever built can be made to work at deep space conditions.

Consequently, we now know how to build future telescopes, which could have the power for the first time to detect the faint fingerprints of life imprinted on a planet going around another star. And because of investments made by the National Science Foundation on the Gemini Telescope and NASA at JPL and elsewhere, we can now use coronagraphs to suppress the light from stars and allow us to actually see other solar systems. And we hope to fly the first truly advanced coronagraph on NASA's WFIRST mission, laying the technical foundation for imaging Earth 2.0 around another star.

We can now bring all of these three advances together, combined with NASA's new SLS capabilities to launch a space telescope that could detect the signs of life on an exoplanet nearly 200 trillion miles away. This would have been science fiction a decade ago. Today, NASA, in one of its four studies for future advanced space observatories, is looking at a large, 15-meter diameter ultraviolet optical infrared telescope we ungainly call LUVOIR, which, with the right commitment, could be ready for launch by the early '30s.

Now, why is such an ambitious telescope with a mirror almost three times the size of James Webb required? First, we have to realize how faint another earth orbiting a neighborhood star would be.

This image, which you can see from here, of course, was taken by NASA's Cassini spacecraft. We already see at the distance of 900 million miles—all we see is a faint, blue dot. That of course is us. At a distance of over 200 trillion miles, that's over 30 light years away, an Earth-like planet is an incredibly faint object. In fact, fainter than the faintest galaxy in this Hubble deep field.

And then we have to understand what we're looking at. You think with 10 to the 23rd stars in the universe—that's one with 23 zeros after it—you would think that life exists somewhere else. Statistically that should be the case. However, if you talk to biologists, these optimistic statistics tell us not so fast. The only place we know life exists is here on Earth. And the only way to actually determine if life exists elsewhere, to find out how unique we actually are, is to go out for ourselves to see. And that is exactly what NASA now has the capabilities to do.

But finding one Earth-like planet won't be enough. We already know two Earth-like planets in our own solar system where there are no visible signs of life, Venus and Mars.

So we're going to have to examine hundreds of exoplanets hunting for those faint signatures of life to find out if habitability exists. If there are habitable planets orbiting around stars near a sun, telescopes like the LUVOIR concept will certainly find at least one. If a LUVOIR does not detect any signs of habitability, we will know that life as it exists on our home planet is extremely rare. This, too, would be profound if a somewhat lonely discover for humanity.

NASA and uniquely this nation has laid the foundation, both scientifically and technically, for such a transformative tool for space astronomy. And this is a telescope we can actually now build because of those investments. And it's important to state without the leadership of NASA's Space Mission Directorate, exemplified by Dr. Zurbuchen, and with the support of committees like these, none of this would be possible. We would not be sitting here today making this case.

So let me make an audacious claim, that the discovery of extraterrestrial life would profoundly change history.

Apollo 8's iconic image on the left of the earth from the moon established the United States as the leader in space, science, and exploration that inspired every generation since, including myself. The discovery of a living planet elsewhere in our galaxy, like this artist concept on the right, would have as profound an impact on the 21st Century as Neil Armstrong's first step would have on the moon. And it is this quest that only NASA is capable of doing, recognizing this. This Committee and Congress added the search for life's origins, evolution, distribution, and the future of the universe to NASA's Authorization Act.

We can build on this vision. We can carry the spirit of Apollo into the galaxy. And let me briefly finish. As Carl Sagan so eloquently said, "When our far descendants perhaps centuries, even millennia in the future, look back from their new home planets and hunt for the pale blue dot in the sky, that was us. They will wonder how humble and fragile were our beginnings, how many rivers we had to cross before we found our way." With American vision, with American leadership and optimism, we can find our way. Thank you, Mr. Chairman.

[The prepared statement of Dr. Mountain follows:]

Matt Mountain

President, Association of Universities for Research in Astronomy

Testimony before the Committee on Science, Space and Technology,
Subcommittee on Space

NASA's Next Four Large Telescopes

December 6, 2017

Mr. Chairman and Members of the Subcommittee, thank you for the opportunity to testify about the revolutionary changes under way in Space Science that have the potential to answer the profound question that has haunted humanity for millennia, for as long as we have looked up into a clear night sky and wondered: Are we alone in the Universe?

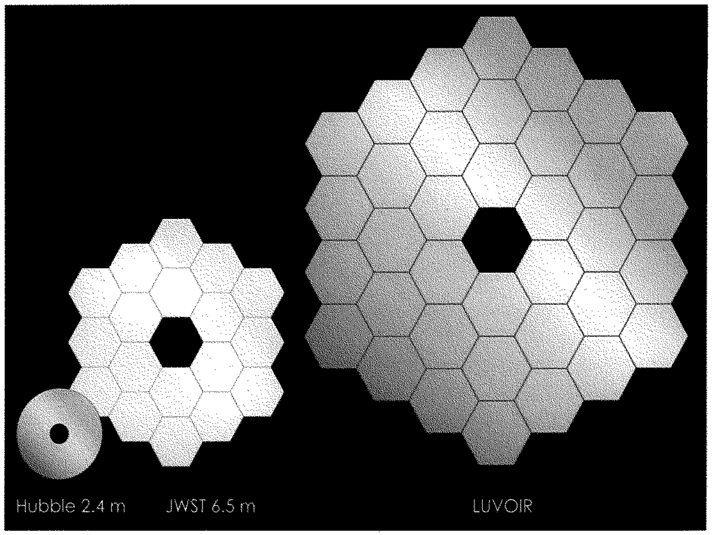
Had I sat before you a mere seven years ago, I could not have told you the sky is full of planets. Now, because of early observations with the Hubble Space Telescope (HST), the transformational observations of a small piece of the sky with NASA's Kepler mission, and ground-based observatories, we now know almost every observable star has a planetary system. With NASA's upcoming Transiting Exoplanet Survey Satellite (TESS), we will be able to refine this view to map out stars in our solar neighborhood that have planets in a habitable zone, perhaps even find some with Earth-sized planets.

If I had sat before you just seven years ago I could not have told you NASA was capable of building the world's largest and most ambitious space telescope, the James Webb Space Telescope (JWST). Today, after staying within budget for the last seven years, even maintaining its cryogenic test program at the Johnson Space Center (JSC) through hurricane Harvey, we now know the complex segmented 21-foot JWST mirror can work in the conditions of deep space. Building the JWST mirror has been an amazing technological accomplishment, and a critical precedent for future space telescopes. Today, because of JWST, we have new mirror technologies that will enable us to build future space telescopes capable of looking deeper and sharper than ever before and, for the first time, of gathering the faint fingerprint of life imprinted on the atmospheres of Earth-like planets around other stars.

Only seven years ago, I could not have told you we would master the complex technologies required to suppress starlight to directly image planets in orbit around their parental stars, and use these coronagraphic technologies on actual working telescopes. Today, because of investments made by the National Science Foundation in the Gemini Observatory telescopes, and by NASA at JPL and elsewhere, we now know coronagraphs work on real telescopes. They are taking real images of nearby solar systems, and studying individual planets with precisions of one part in a million. With JWST we will soon see coronagraphic data of a quality never seen before. And we plan to fly the first truly advanced coronagraph in space on NASA's Wide Field Infrared Survey Telescope (WFIRST) mission, complete with adaptive optics and active wavefront control required to precisely image some of the faintest objects ever observed. This will herald in a new era of high-performance space coronagraphy, giving a further 100 times improvement in our ability to distinguish the faint glow of planets in the presence of their bright host stars. With WFIRST we will be laying the technical foundation for imaging Earth 2.0 around another star.

What is so exciting today is that we have the very real potential to bring these incredible advances together: the latest science discoveries on exoplanets, the technologies of large segmented telescopes, and our ability to fly and operate high-performance coronagraphs in space, with NASA's unique new capabilities to launch a space telescope with the ability to detect signs of life on an exoplanet, nearly 200 trillion miles away!

Imagine a telescope that has the ability to directly image and characterize hundreds of planets outside our solar system - one that can tell us with great certainty whether there are other worlds capable of supporting life as we know it. This is within our reach for the first time in human history. This is where NASA's audacious space science program is leading us, to a telescope that can provide a definitive answer to the question: *Are we alone*?

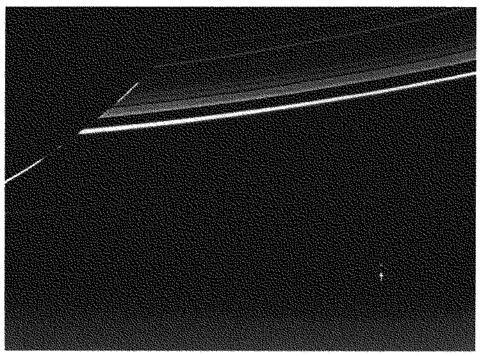


Such a transformative tool is not one of science fiction or even the distant future. NASA, in one of its four studies for future advanced space observatories is looking at a Large Ultraviolet/Optical/Infrared (LUVOIR) Telescope, which with the right commitment, could be ready for launch by the early 2030s. Each of NASA's Great Observatories had a transformational Mission. Hubble's was to understand the age and size of our Universe. JWST is designed to explore our Origins: the origins of Galaxies, of Stars buried in their placental clouds, and the origins of planetary systems like our own. Building on the scientific discoveries and advanced technologies developed for HST, JWST, and, WFIRST, the Mission for this new, Large Ultra-Violet/Optical/Infrared "Great Observatory" would be to complete our long journey, to discover if we are alone in the universe. And, along the way, observe the Universe in unprecedented "high-definition." In the words of Noble Laureate Riccardo Giacconi, for the first time to observationally tackle *"the evolution of the Universe in order to relate causally the physical condition during the Big Bang to the development of RNA and DNA."*

NASA's great observatories have shown us that it is not enough just to wonder – we have to go out and observe; we have to go and explore the Universe with tools only NASA can provide.

Why is such an ambitious telescope, with a mirror almost three times larger than JWST's mirror, required?

First, we have to realize how faint another Earth orbiting a neighborhood star would be.



NASA's Cassini Spacecraft took this image our planet while orbiting Saturn. Already at this distance, some 900 million miles all we see is a small pale blue dot. Now imagine you are looking for this same blue dot, but now from a 222 thousand times further away, a distance of 200 trillion miles, the distance to our nearest stars.

At a distance of over 200 trillion miles (or just over 30 light-years), an earth-like planet, the same color and brightness as our Earth is an incredibly faint object: in fact fainter than the faintest galaxy in the Hubble Deep Field. It will take a large telescope, far larger than the Hubble Space Telescope to collect and analyze the faint photons from another earth. Even with a 15m space telescope we would only get one photon per second from such another Earth: over the course of this testimony such a space telescope two and half times larger than JWST, would only collect 300 extra-terrestrial photons. And unfortunately, at this distance, an Earth 2.0 is incredibly close to its Sun 2.0, as seen from here on Earth 1.0, less than the width of a human hair held at arm's length.....if your arm is two football fields long. Only with something as large as LUVOIR can we have both the photon gathering power **and** the spatial resolution to pull this this observation off.

And then we have to understand, what are we looking for?

With all of these discoveries and with 10^{23} stars in the universe, it would seem statistically very likely that life exists in some of these alien planetary systems. Indeed, in June of last year, *The New York Times* acknowledged this new perspective with an optimistic piece titled, "Yes, There Have Been Aliens."

But not so fast. These optimistic statistics and promising discoveries can't tell us *for sure* that we aren't alone. The only place we *know* life exists is here on Earth. And yes, here on our planet life is tenacious: thriving 20,000 feet down, where strange organisms flourish on deep-sea vents without sunlight or oxygen; and 20,000 feet up, where cacti and insects have found a niche in the Atacama Desert. And yes, it is also resilient, adapting to ponds as corrosive as battery acid and feeding off radioactive waste in Chernobyl. And yet, we don't know how life actually *began* here on Earth. Modern DNA analysis tells us that complex life, anything beyond a single cell organism, resulted from a random "event" in which two cells came together to form eukaryotes (cells with a nucleus) – something that apparently happened only once in the 4.5- billion-year history of our planet. Every worm on a deep-sea vent, or cactus eking out an existence in the high Andes, every human who hunted on the plains or stood on the moon, all owe their existence to a single chance meeting of two cells that learned to get along.

There may be billions of Earth-like planets out there that are abundant with all the elements for life, but that doesn't mean that there is life, let alone *complex* life on any of them. Today we can't calculate how likely Life might be, the only way to determine how unique we are is to go see for ourselves, and this is exactly what NASA now has the capability to do

We know, for example, from experience with the currently hostile environments of Venus and Mars that not all Earth-sized planets orbiting in the habitable zones of their stars are equally hospitable to life. Determining whether an exoplanet is habitable requires careful, and rather detailed analysis of the planet's atmosphere.

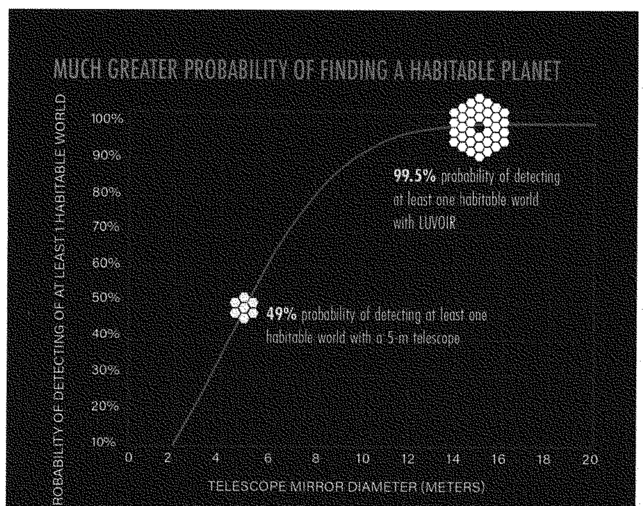
LUVOIR, with its large segmented mirror, powerful light-blocking coronagraph, and precision spectroscopic instrumentation, will be uniquely outfitted to measure and monitor changes in the atmospheric compositions of dozens of Earth-sized exoplanets, revealing the presence–or absence–of molecules like water, carbon dioxide, ozone, and oxygen, which are known to support life on Earth.

This is the first time in human history that we have all the tools to go and see - to find an answer.

But finding one Earth-like planet will not be enough.

When designing a mission to detect life outside our solar system, we must assume that only a small fraction of exoplanets are actually habitable. Detecting life–or ruling it out– with confidence requires sampling hundreds of planetary systems, a feat possible only with a large telescope like LUVOIR.

Examining hundreds of exoplanets allows us to put important constraints on how common life is in the universe. If there are habitable planets orbiting around stars near a Sun, LUVOIR is almost certain to find at least one. If LUVOIR does not detect any signs of habitability, we will know that life, as it exists on our home planet is, as biologists' think, probably extremely rare. This too would be a profound discovery for humanity.

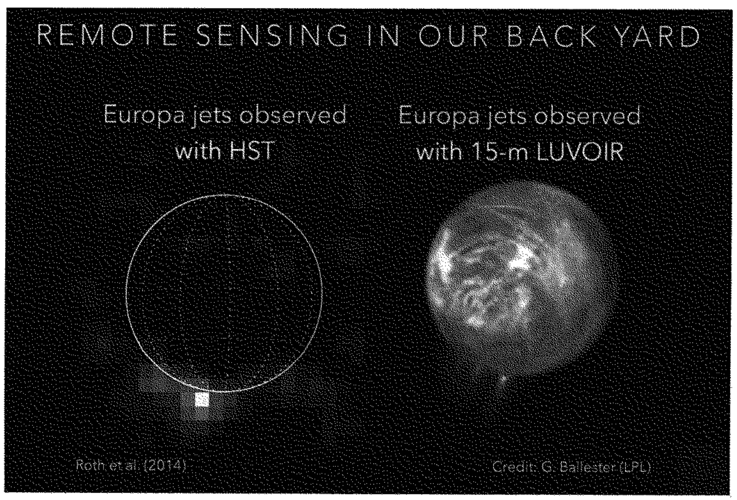


Probability of finding at least one habitable planet, assuming 10% of candidate planets are habitable: The larger the mirror, the more likely we are to detect signs of life outside the solar system.

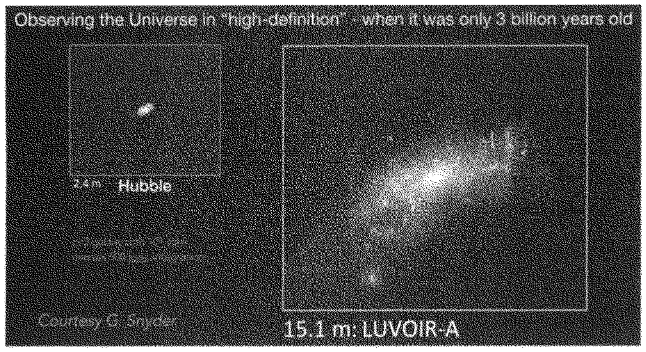
As my colleague Ken Sembach articulated in an article for Space News, titled, "In Searching for Life, Go Big or Stay Home": *"We could build a smaller telescope and hope we detect a handful of potentially Earth-like planets and hope that one is habitable. But hope is not a strategy."*

A transformative tool for Space Astronomy.

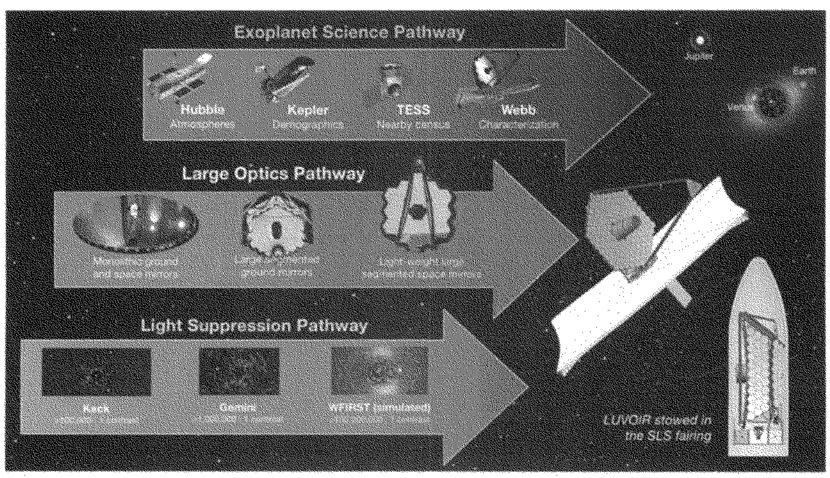
Though the focus of this testimony has been on the future of exo-planet research, quite crucially the LUVOIR mission is envisioned as a Great Observatory in the era beyond Hubble and JWST. At this point on the ground we will have at least one enormous 39m ground-based telescope, maybe even three. With its optical diffraction limited 10m -16m aperture, and unparalleled UV sensitivity, which is possible only from space, a LUVOIR will still outperform even the largest ground based telescopes, retaining US leadership in observational astronomy.



From being able to continuously observe planets within our own solar-system in unprecedented detail, to exploring how galaxies like our own built up over Cosmic time - LUVOIR would be a transformative Great Observatory.



NASA has laid the scientific and technological foundations for this next Great Observatory over the course of its incredible 50-year history of scientific discovery. Without the "jewel" of the Science Mission Directorate in NASA's portfolio, none of the discoveries we have made to date, with mission like Hubble or Kepler, or to be made in our audacious future, would be possible.



The evolutionary path to a 10m - 16m UV/Optical/IR space telescope capable of providing a transformational tool for Astrophyscis, and capable of characterizing sufficient exo-Earths to confirm the null hypothesis: we are alone*

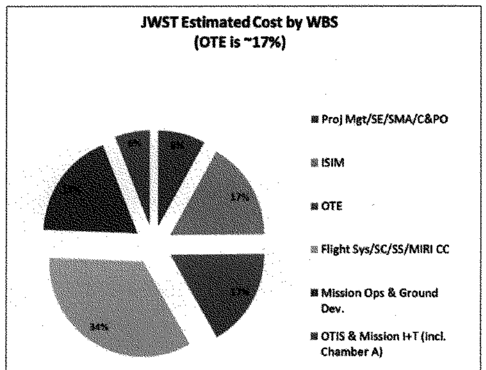
** Requirement from the Kavli IAU Meeting on Global Coordination: Future Space-Based Ultraviolet-Optical-Infrared Telescopes*

How can such an ambitious space telescope be affordable?

"Affordability" begins with concerted technology investments, which of course have already begun with missions like JWST, WFIRST, and investments by some of our aerospace partners. Astronomers are not alone in wanting large optical imaging systems in space. However, it's important not to fall into the tempting trap of assuming the cost of space telescopes scale simply with telescope diameter.

Several factors drive, and have driven, the actual costs of space missions like HST, JWST or even WFIRST.

First, numerous studies have shown that many more factors than the size of the telescope mirror drive the costs of a space telescope. For example, an ananlysis of the cost of JWST and its subsystems (figure below) shows the cryogenic 6.5 mirror diameter mirror (the Optical Telescope Element, or OTE) contributed only 17% of the cost of JWST. The flight systems required for an L2 orbit, and cooling the entire spacecraft to - 400° F and JWST's instrument package (ISIM) together represented over 50% of the total cost.



Courtesy Lee Feinberg

Figure showing the breakdown of NASA's JWST costs by Work Break Down Structure (WBS) element.

The cost of JWST's mirror, described by the Optical Telescope Element (OTE), the accounts for only 17% the cost of JWST.

The Instruments (ISIM) and Flight Systems (Sys/SC/SS/MIRI CC) account for over 50% of the cost of JWST.

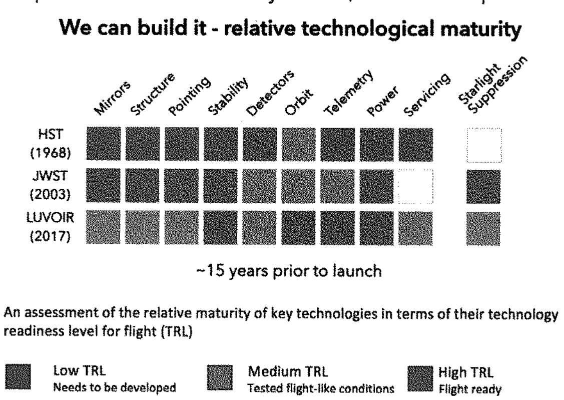
Second, as was the case for JWST whose early funding was artificially constrained in the crucial early years of technology and design development, without an optimal funding profile costs will be increase. Once an optimal funding profile was finally agreed for JWST, it has remained inside its cost-envelope for the last seven years.

A point re-iterated in fact by the WFIRST Independent External Technical/Management/Cost Review (WIETR) that a factor in this missions cost growth was a less-than-optimal funding profile.

Consequently there is no engineering or technology basis for the statement, "building a telescope three times larger than JWST will cost at least three times more than JWST". *This scaling didn't work extrapolating the costs from HST to JWST.*

As my colleague Martin Frederick (from Northrop Grumman) has pointed out, the first step in comparing the cost of missions across the decades is to appreciate the compounding effects of simple inflation. Thirty years ago, in late-1980 dollars (assuming NASA full cost accounting) HST cost NASA approximately $3B. Taking that same mindset ("back in the day, this would have cost $3B"), and simply indexing the HST $3B profile to 2007 dollars, the year JWST was first costed, that same profile would have cost $8.4B. This is comparable to the cost of JWST today, but JWST has a mirror diameter almost three times larger than HST, and will have infrared capabilities 100 times more sensitive than HST.

The key to JWST's tremendous capabilities as compared to HST is that in order to build the cryogenically cooled 6.5m JWST, NASA had to "invent" ten new technologies. For a warm (or non-cryogenic) telescope like LUVOIR, as I have discussed above with JWST and WFIRST as technology demonstrators, NASA is already building up considerable heritage in the key technologies. It is interesting to qualitatively compare the relative maturity of HST, JWST and a potential LUVOIR.



An assessment of the relative maturity of key technologies in terms of their technology readiness level for flight (TRL)

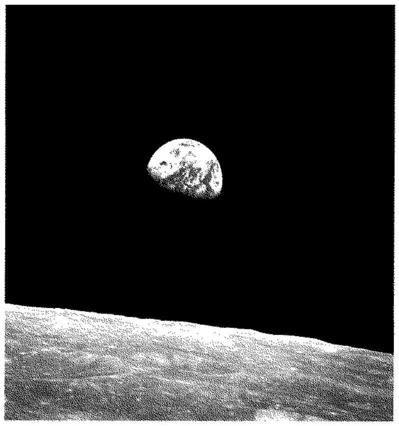
The fundamental point is that the only credible approach to estimating the cost of a mission of the scale of LUVOIR is to invest in the appropriate technologies ahead of time, undertake comprehensive analysis of all the systems required for a telescope to be launched around 2030, and then, ***crucially***, undertake to fund the mission with an optimal funding profile.

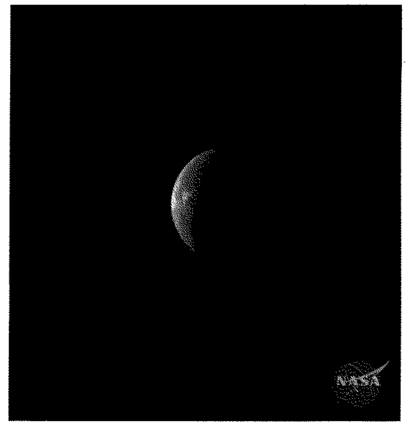
In this time frame, we also have to take into account the capabilities of NASA's Space Launch System (SLS). The SLS has the potential to change the paradigm for ambitious space science missions. For example, the SLS provides the means for launching deployable telescopes three to four times larger than JWST. SLS will be able to lift as much as 130 metric tons of payload to low Earth orbit. This means that more conventional materials could be used in the spacecraft and observatory design. Ultra-lightweight components could be replaced with heavier and more rigid structures. This can greatly simplify design and testing, and significantly reduce the cost of such space telescopes.

The discovery of extra-terrestrial life would have as profound an impact on the twenty-first century as Neil Armstrong's first step on Moon walk had in the twentieth century.

Answering the question" Are we alone in the Universe?" is the space science challenge of the 21st century. And this is a quest only NASA is uniquely capable of undertaking. In 1969, NASA inspired the world with Neil Armstrong's foot print on the Moon. The author Yuval Noah Harari wrote in his best-selling book on the history of our species, Sapiens: *"This was not merely a historical achievement, but an evolutionary and even cosmic feat."*

This year Congress and the administration passed the NASA Authorization Act. In this bill, this sub-Committee and subsequently Congress added a momentous phrase to the agency's mission: **"the search for life's origins, evolution, distribution, and future in the universe."** It's a short phrase, but a visionary one. It acknowledges at this threshold of the 21st century that NASA, and this nation, once again have the opportunity to "change the world."


20th Century NASA


21st Century NASA

Let me end with two images. On the left the iconic view of our world taken on Christmas by the Apollo 8 Astronauts, signaling to the world, the United States was on its way to "a cosmic feat." On the right is an imaginary image taken with a far future NASA spacecraft visiting another blue planet, Earth 2.0, first discovered with a large LUVOIR-like space telescope launched as a follow-on to JWST and WFIRST.

As Carl Sagan so eloquently said: *"when our far descendants perhaps centuries, even millennia in the future, look back from their new home planets, they will wonder how humble and fragile were our beginnings, how many rivers we had to cross before we found our way."* Our science points the way to satisfy humanity's insatiable curiosity; we have the technologies to build and launch telescopes like LUVOIR; now we must determine if we have the will as a nation to take our first, tentative steps to crossing that first interstellar river, to find our way to the first Earth 2.0.

For decades, the United States was an established world leader in space science and the exploration of the Universe. An ambitious but affordable mission to answer the grand question of the cosmos will continue to keep us at the forefront of science and technology for decades to come.

Mr. Chairman, thank you for your support, and that of this Subcommittee. I would be pleased to respond to any questions you or the other members of the Subcommittee may have.

Short Biography: Dr. Matt Mountain

Dr. Matt Mountain is the current President of the Association of Universities for Research in Astronomy (AURA.) AURA is a not-for-profit consortium of 44 US Universities and 4 International affiliates which builds and operates telescopes and observatories for the National Science Foundation (NSF) and the National Aeronautical and Space Administration (NASA). Facilities under AURA's management include the Gemini Observatory, the National Optical Astronomical Observatory (NOAO), the National Solar Observatory (NSO), the science operations for the Hubble Space Telescope and James Webb Space Telescope. AURA is also responsible for the construction of the Daniel K. Inouye Solar Telescope on Haleakalā, Hawaii and the Large Synoptic Survey Telescope (LSST) on Cerro Pachón in Chile. AURA has a staff of over 1,400 scientists, engineers, and administrators with an annual operating budget of approximately $300M.

Prior to this, Mountain was the Director of the Space Telescope Science Institute (STScI.) STScI is responsible for the science operations and education and public outreach for the Hubble Space Telescope (HST), the creation and implementation of the James Webb Space Telescope (JWST) science operations center and running NASA's Mikulski Archive for Space Telescopes (MAST). The Institute has a world-renowned science faculty of over 90 researchers and an engineering and administrative staff of approximately 600 with an annual budget of $140M. The Institute was established in 1981 as a community-based science center, operated for NASA by AURA. Mountain is still a Telescope Scientist for JWST, and a member of the JWST Science Working Group.

Before joining STScI in 2005, Mountain was the Director of the International Gemini Observatory and led the team that designed, built, and brought into operation the two Gemini telescopes on Mauna Kea, Hawaii, and Cerro Pachón, Chile.

His research interests have included star formation, advanced infrared instrumentation, and the capabilities of advanced telescopes. He received his degree in Physics in 1979 and Ph.D. in Astrophysics in 1983 both from Imperial College of Science and Technology, University of London. Mountain has published over 100 research papers, articles, and reports. He is a Professor in the Department of Physics and Astronomy at the Johns Hopkins; fellow of the American Association for the Advancement of Science, and the Royal Astronomical Society; and a member of the American Astronomical Society, and the International Society for Optical Engineering.

Chairman BABIN. Thank you very much. Now I'd like to recognize Dr. McKee for your testimony for five minutes.

TESTIMONY OF DR. CHRIS MCKEE, PROFESSOR EMERITUS OF ASTRONOMY, PHYSICS, UNIVERSITY OF CALIFORNIA, BERKELEY, ON BEHALF OF THE NATIONAL ACADEMIES OF SCIENCES, ENGINEERING AND MEDICINE

Dr. MCKEE. Chairman Babin, Ranking Member Bera, Chairman of the Committee, Mr. Smith, and Ranking Chair Johnson, thank you very much for the opportunity to appear before you today in my capacity as a member of the Committee on Astronomy and Astrophysics, the CAA, of the National Academies of Sciences, Engineering and Medicine. CAA is one of five subcommittees of the Academies' Space Studies Board that span the science disciplines supported by NASA. Each of the five subcommittees is charged to assist the federal government by providing advice on the implementation of Decadal survey recommendations. As you know, the National Academies' Decadal surveys, which are mandated by law, provide NASA with consensus advice from the scientific community on proposed science priorities for the decade ahead.

I have the honor of serving on the CAA, and I was also one of the co-chairs of the 2001 Decadal survey in astronomy. The highest recommendation in our report was the James Webb Space Telescope, JWST, a truly remarkable feat of engineering that is expected to deliver ground-breaking scientific capability beyond that envisioned when we recommended it.

Chairman Babin, I would like to thank you and the Committee for giving me the opportunity to present to you today some of the perspectives on the status of NASA's program in astrophysics, drawing in particular on the Academies' 2016 report, New Worlds, New Horizons: A Midterm Assessment. This report concluded that already in the first half of the decade, scientists and teams of scientists working with these cutting-edge instruments and with new capabilities in data collection and analysis have made spectacular discoveries that advance the NWNH vision.

While these discoveries are really remarkable, the fact that they occurred is not. The Congress, the executive, and the research community have relied on the independent and non-advocacy convening power of the National Academies to develop a national consensus on which science space missions NASA should pursue. This process, over a period of nearly 60 years, has led to the United States developing clear leadership across all the fields of space science. This is why the Congress has repeatedly instructed NASA and the executive to use the Decadals as the foundation of the agency's strategic planning in space science.

An essential feature of the Decadal process is it involves a broad cross-section of the community. In the case of the 2010 Decadal survey in astronomy and astrophysics, the Academies appointed nearly 200 astronomers to the survey committee, the supporting panels, and the working groups. Hundreds of additional astronomers provided input. In fact, I would venture to guess that a significant fraction of the entire astronomical community participated.

The committee then undertook the hard and painful task which was necessitated by the relatively severe financial constraints under which the agencies were expected to have to operate of prioritizing the many exciting and realizable activities presented to it.

Mr. Chairman, today NASA is implementing the Decadal survey. The Wide-Field Infrared Survey Telescope, WFIRST, which was the 2010 Decadal's highest-ranked large space telescope is "designed to settle essential questions in both exoplanet and dark energy research and will advance topics ranging from galaxy evolution to the study of objects within our own galaxy."

The midterm report underscored the continuing scientific case for the pursuit of this mission. The report noted that implementation of WFIRST with a larger mirror than it envisioned at the time of the Decadal's prioritization with larger infrared detectors, and with the addition of a coronagraph makes WFIRST an ambitious and very powerful facility.

However, because the risk of cost growth in WFIRST could distort the NASA program balance and limit options for the next Decadal survey, the midterm report called for an independent and technical, management, and cost assessment of WFIRST. That assessment has been carried out, and the descoping effort is now under way.

Meanwhile, it's also worth noting that the midterm report endorsed NASA's plans for executing the second priority recommendation of the 2010 Decadal, the enhancement of the Explorer program. The Explorer program is currently supporting the development of the Transiting Exoplanet Survey Satellite, TESS, which is scheduled for launch next March. NASA is also implementing the third and fourth high-priority recommendations in partnership with our European colleagues at ESA through participation in the Athena x-ray telescope and in the LISA gravitational wave observatory.

LISA will open a new window on the cosmos by measuring the ripples in space-time produced by the merger of black holes which are far larger, more massive than can be detected with the NSF-supported LIGO facility. That facility has confirmed Einstein's theory of gravity and solved the mystery of the source of many of the elements in the periodic table beyond iron, such as gold and uranium.

The next Decadal is expected to start in about a year's time, and at the CAA we have heard how NASA is supporting teams of astronomers and engineers to develop mission concepts for both flagship missions and moderate-scale missions. This methodical approach to preparing the community for the Decadal is, in my personal opinion, vitally important. The CAA is at the same time preparing to release the first call for white paper inputs from the community in advance of the survey so that when the chair is appointed, she or he will have fresh community input on the science what is nominally called Astro 2020.

Mr. Chairman and the members of the Committee, the bottom line result of the Decadal survey process in astronomy and astrophysics and indeed in all the scientific fields supported by NASA is that the United States has reaped the benefits of this community-based process that the Academies conduct on behalf of the nation under its unique charter from Congress. I'm here today to discuss why this process works as well as it does and to answer any questions you may have. Thank you.

[The prepared statement of Dr. McKee follows:]

Testimony of

Dr. Christopher F. McKee, University of California, Berkeley

Member, Committee on Astronomy and Astrophysics
Space Studies Board
Board on Physics and Astronomy
Division on Engineering and Physical Sciences
The National Academies of Sciences, Engineering, and Medicine

before the

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

December 6th 2017

Chairman Babin, Ranking Member Bera, and members of the committee:

Thank you for the opportunity to appear before you today in my capacity as a member of the Committee on Astronomy and Astrophysics (CAA) of the National Academies of Sciences, Engineering and Medicine. CAA is one of five subcommittees of the Academies' Space Studies Board that span the science disciplines supported by NASA. In the case of the CAA, the committee is also a subcommittee of the Academies' Board on Physics and Astronomy, so that the one committee can cover all of astronomy and astrophysics, including programs supported by the National Science Foundation and the Department of Energy. Each of the five subcommittees is charged to assist the federal government in integrating and planning programs in space sciences by providing advice on the implementation of decadal survey recommendations. As you know, the National Academies' decadal surveys—mandated by law—provide NASA with consensus advice from the scientific community on proposed science priorities for the decade ahead.

I have the honor of serving on the CAA and, as you mentioned in your introductory remarks, I was one of the co-chairs of the 2001 decadal in astronomy and astrophysics. The highest recommendation in our report, *Astronomy and Astrophysics in the New Millennium*, was the James Webb Space Telescope (JWST), a truly remarkable feat of engineering that is expected to deliver groundbreaking scientific capability beyond that envisioned when we recommended it. I am also honored to be a member of the CAA when, under a new charter from the Academies, it is able to issue fast-turn-around reports that will provide guidance to federal agencies that support astronomy and astrophysics research.

Chairman Babin, I would like to thank you and the committee for giving me the opportunity to present to you today some perspectives on the status of NASA's program in astrophysics—drawing in particular on the Academies' 2016 report *New Worlds, New Horizons: A Midterm Assessment* which came to some very important conclusions on the status of the implementation of the 2010 decadal and looked forward to the next decadal. I'd like to start by reading a quote from that report:

> *New Worlds, New Horizons in Astronomy and Astrophysics (NWNH), the report of the 2010 decadal survey of astronomy and astrophysics, put forward a vision for a decade of transformative exploration at the frontiers of astrophysics. This vision included mapping the first stars and galaxies as they emerge from the collapse of dark matter and cold clumps of*

hydrogen, finding new worlds in a startlingly diverse population of extrasolar planets, and exploiting the vastness and extreme conditions of the universe to reveal new information about the fundamental laws of nature. NWNH outlined a compelling program for understanding the cosmic order and for opening new fields of inquiry through the discovery areas of gravitational waves, time-domain astronomy, and habitable planets. ...... Already in the first half of the decade, scientists and teams of scientists working with these cutting-edge instruments and with new capabilities in data collection and analysis have made spectacular discoveries that advance the NWNH vision.

Mr. Chairman, while the discoveries are remarkable, the fact that they have occurred is not: The Congress, the Executive and the research community have relied on the independent and non-advocacy convening power of the National Academies to develop a national consensus on which scientific space missions NASA should pursue across the programs in the Science Mission Directorate. This process, over a period of nearly 60 years, has led to the United States developing clear leadership across all the fields of space science, which is why the Congress has repeatedly instructed NASA and the Executive to use the decadals as the foundation of the agency's strategic planning in space science. Every prioritization process produces winners and losers, but there is broad support in the scientific community for the consensus-building process that has given us winners such as Hubble, Cassini, and Curiosity.

Mr. Chairman, members of the committee, as you well know the decadal process involves a broad cross section of the community. In the case of the 2010 decadal survey in astronomy and astrophysics, the Academies appointed nearly 200 astronomers to the survey committee, supporting panels and working groups. They received input from hundreds of astronomers, who submitted over 700 white papers describing opportunities for the current decade. The committee identified 20 key science questions that provided a framework for evaluating a compelling program of high-priority research activities. The science goals for the decade were focused into three science objectives, labeled "Cosmic Dawn," "New Worlds," and "Physics of the Universe." The committee then undertook the hard and painful task, necessitated by the relatively severe financial constraints under which the agencies were expected to have to operate, of prioritizing the many exciting and realizable activities presented to it. The resulting program is described in the 2010 decadal report.

Mr. Chairman, today NASA is implementing the decadal survey. The *Wide-Field Infrared Survey Telescope* (WFIRST) was the 2010 decadal's highest-ranked large space observatory with science goals that drew on and combined a set of mission concepts proposed by the community into a unified science program that, as the decadal report said, is "designed to settle essential questions in both exoplanet and dark energy research, and will advance topics ranging from galaxy evolution to the study of objects within our own galaxy." The midterm report underscored the continuing scientific case for the pursuit of this mission and its planned implementation with a larger mirror than envisioned at the time of the decadal's prioritization, saying that the 2.4-meter telescope, larger infrared detectors, and addition of a coronagraph make the 2016 design of WFIRST an ambitious and powerful facility. However, because the risk of cost growth in WFIRST could distort the NASA program balance and limit options for the next decadal survey, the midterm report called for an independent technical, management, and cost assessment of WFIRST. The report recommended that, if the mission cost estimate were high enough to compromise the scientific priorities and the balanced astrophysics program recommended by the decadal, then NASA should descope the mission. At our last CAA meeting in October, we heard the results of that assessment and the resulting efforts requested by NASA from the mission team to reduce the planned cost of the mission. The committee will no doubt hear at its March meeting the outcome of those efforts, and we may be asked to comment in a CAA report.

Meanwhile Mr. Chairman, it is also worth noting that the midterm report endorsed NASA's plans for executing the second priority recommendation of the 2010 decadal, the enhancement of the

Explorer program, and that NASA should execute at least four Explorer Announcements of Opportunity during the 2012-2021 decade, each with a Mission of Opportunity call, and each followed by mission selection. The Explorer program is currently supporting the development of the *Transiting Exoplanet Survey Satellite* (TESS), scheduled for launch in March 2018. This satellite will use similar techniques to the highly-successful Kepler telescope, but it will observe bright, relatively nearby stars over the whole sky, thus identifying exoplanet targets that are ideal for follow up by the *James Webb Space Telescope* and other facilities.

NASA is also implementing the third and fourth high-priority recommendations in partnership with our European colleagues at ESA through participation in the Athena x-ray telescope and in the ambitious and exciting opportunity that will be provided by the LISA gravitational wave observatory. LISA will open a new window on the cosmos by measuring the ripples in space-time produced by the merger of black holes much more massive than can be detected by the NSF-supported LIGO facility, which has confirmed Einstein's theory of gravity and solved the mystery of the source of many of the elements in the periodic table beyond iron—such as gold and uranium.

There are many other exciting aspects to NASA's execution of decadal survey recommendations that I could address, but I have concentrated on the highest priorities of the recent decadal survey since they set the context for the next decadal that is expected to start in about a year's time.
At the CAA we have heard in presentations, made over the last 2-3 years, how NASA is supporting teams of astronomers and engineers to develop mission concepts for the large strategic class of missions—sometimes called flagship missions—and for moderate-scale missions. The scientific cases being developed for each telescope are compelling and ambitious. This methodical approach to preparing the community for the decadal is, in my personal opinion, vitally important. The CAA is at the same time preparing to release the first call for white paper inputs from the community in advance of the survey so that when the chair is appointed, she or he will have fresh community input on the science when designing the plan to execute what is nominally called Astro2020.

It would, Mr. Chairman, be remiss of me to provide any comparisons among the missions that will be proposed to the decadal survey as I have complete confidence in the ability of the survey process to assess the science cases for each, the technical challenges each bring, and the likely affordability of the missions. This is what my community has been doing now for nearly 60 years, and each time the result has been a flexible and impactful program that pursues large strategic-class missions that can take over a decade to develop and launch and that produce major scientific results unmatched by any other nation, as well as pursuing smaller, rapid response missions like the TESS exoplanet mission I discussed earlier.

Mr. Chairman and members of the committee, the bottom line result of the decadal survey process in astronomy and astrophysics—and in the other scientific fields supported by NASA—is that the United States has reaped the benefits of this community-based process which the Academies conduct on behalf of the nation under its unique charter from the Congress. I am here today to reiterate why this process works as well as it does, and to answer any questions you may have.

Thank you.

Biography

Dr. Christopher McKee

University of California, Berkeley

Christopher McKee received his AB degree from Harvard in 1963, and his PhD in physics from Berkeley in 1970, where a Hertz Fellowship supported him. After a year as a postdoctoral fellow at Caltech and several years as an assistant professor of astronomy at Harvard University, he joined both the Department of Physics and the Department of Astronomy at Berkeley, where he has been since 1974. He has carried out theoretical investigations of a wide variety of astrophysical phenomena, ranging from the interstellar medium of the Galaxy to quasars and cosmic gamma-ray bursts. His current research focuses on the structure and evolution of molecular clouds and the star formation that occurs within them: How do low mass stars like the Sun form? How do the massive stars that create most of the heavy elements form? What determines the rate of star formation in galaxies? How did the first stars form? With Richard Klein and their joint students and post docs, he studies these problems with high-resolution numerical simulations. He and his collaborators developed the turbulent core model for massive star formation and the first comprehensive theory for the rate of star formation in galaxies.

He has received a number of honors for his work: He is a member of the National Academy of Sciences, a fellow of the American Academy of Arts and Sciences, a fellow of the American Association for the Advancement of Science, and a fellow of the American Physical Society. He has been the Sackler Lecturer at Harvard University, at the University of Toronto, and at Tel Aviv University, the Bahcall Lecturer at Tel Aviv University, and the Antoinette de Vaucouleurs Medalist and Lecturer at the University of Texas. He was awarded the Henry Norris Russell Lectureship by the American Astronomical Society in 2016.

He has held a number of administrative positions, including serving as founding director of the Theoretical Astrophysics Center (1985), the director of the Space Sciences Laboratory (1985-1998), the chair of the Physics Department (2000-2004), the Interim Dean of Mathematical and Physical Sciences (2014), and the Interim Vice Chancellor for Research (2015-16). With Joseph Taylor of Princeton University he co-chaired the *Astronomy and Astrophysics Decadal Survey* (1998- 2001) and is currently a member of the Academies' *Committee on Astronomy and Astrophysics* that is charged to provide advice to the federal government on the implementation of the 2010 *New Worlds New Horizons* decadal survey in astronomy and astrophysics.

Chairman BABIN. Thank you very much for your testimony, Dr. McKee. The Chair would like to recognize himself for five minutes for questions.

Dr. Zurbuchen, NASA indicated that the delay to JWST is a result of issues identified in integration and testing, but there was also a potential conflict in French Guiana with the European BepiColombo mission. Why was the decision made to launch the $8 billion JWST on the European Ariane 5 rocket instead of a reliable U.S. launch vehicle? Was cost the only consideration? And what are the risks associated with the transporting of JWST to the European launch site located in South American French Guiana?

Dr. ZURBUCHEN. Thanks for your question, Mr. Chairman. Part of the decision to go with this other launch vehicle, of course, was cost. And at that moment in time, you remember of course, I was not sitting here when that decision was made. Cost was an important factor but so was international collaboration that's really part of the James Webb Space Telescope. It's part of the telescope itself and instruments. We have important international collaborations that really contribute to the leadership that we have in space astrophysics. So we don't believe that there's a conflict of leadership for the United States and some of these collaborations.

I will submit, if so desired, Mr. Chairman, more information for the record——

Chairman BABIN. Yes.

Dr. ZURBUCHEN. —on the details of that decision and all of this. You should know that the path to that launch site has been under consideration, and in detail, I've heard a briefing for every part of that. And we understand what the risks are. Indeed though I'm comfortable with it.

Chairman BABIN. I understand they're going to have to even change bridge heights and things like that. Is that the case?

Dr. ZURBUCHEN. There's a number of things that we have to do for testing with Webb. Some of the tests we actually wanted to do in some other districts we didn't do because of bridges. In some cases, yes. Some bridges might be lifted or some roads will be enlarged for that. Again, I'll provide the details.

Chairman BABIN. Right. One of the lessons learned that GAO highlights is the need to manage cost and schedule performance for large projects to limit the impacts to the entire science mission portfolio. What ways can NASA balance its portfolio better and ensure that problems and large programs do not overwhelm the smaller ones without losing sight of science objectives, Dr. Zurbuchen?

Dr. ZURBUCHEN. I believe that what we did with WFIRST is exactly what we should be doing to ensure that balance. I mean, I'm committed to keeping that balance in place through the astrophysics portfolio as well as the other disciplines where similar recommendations are provided from their respective Decadals. And I believe that what is required, especially prior to Key Decision Point C which is what Tom Young talked about, it's absolutely important to create management processes to make sure that these missions don't blossom without boundary, without limit, into bigger missions. So the independent review as well as the action that I took is precisely motivated, not because of anything that we don't like about the mission, but motivated by the importance of creating that balance and keeping it for the years to come.

Chairman BABIN. Okay. Thank you. Now, Dr. McKee, the cost estimates for both JWST and WFIRST increased drastically from the time the Academies recommended them as part of the Decadal survey. Does the Academy provide any recommendations on the maximum cost a program should grow to before it compromises other astronomy and astrophysics priorities? And does the Academy recommend any capabilities to descope if problems are encountered during formulation or development?

Dr. MCKEE. Let me begin by discussing the first of the projects you mentioned, James Webb. At that time, we did not have the cost control measures that NASA has implemented since, and as I think has been noted, there was a drastic increase in the overall cost of that mission.

At the time of the 2001 Decadal survey, we did not anticipate such a cost growth. By the time of the 2010 Decadal survey, there was a much greater awareness of the impact of these large missions, and as a result, that Decadal survey considered several different scenarios for the budget of the program. However, to my knowledge, they did not explicitly put in any, you know, hard-and-fast rules as to how you would descope.

As the issue of the problems come up with the NASA budget, the importance of maintaining a balanced program is very high on the priority list for the Academies, and they have been, you know, working with NASA to try to maintain that.

Chairman BABIN. I have several more questions, but I'm out of time. So we're going to go to the gentleman from California, the Ranking Member, Mr. Bera.

Mr. BERA. Thank you, Mr. Chairman. In my opening comments I talked about, you know, just gazing at the sky and, you know, what Hubble allowed us to do was those fuzzy patches that we see out there prove that those galaxies full of millions or billions of stars existed. It also proved that the universe was expanding.

I guess, Dr. Zurbuchen, as I'm thinking about, you know, TESS, James Webb, and WFIRST, science building on itself, I just want to make—with TESS, we'll do that all-sky survey. We'll learn more about exoplanets and find more exoplanets. With James Webb, am I understanding this correctly, we'll look sometimes backwards in time and look at star formation and, you know, trace the evolution of these galaxies from birth to death and learn much more about our universe? And then in the WFIRST program, you know, this dark energy that is expanding our universe and the purpose of WFIRST is to better understand that dark energy as well as to continue to learn more about the exoplanets that are out there as, you know, we search for life, as we search for, you know, what else is out there. Am I thinking about that correctly? One building on the next, each mission informing the next mission. For those folks that are watching at home, because I know they're riveted to their televisions, you know, trying to figure out where we go next, and so if we're building one mission on the next, if we think about the Decadal survey which is our objective way of—you know, as much as Decadal informed us to do James Webb, Decadal informed us that we should focus on WFIRST. You touched on the four possibilities going into this next Decadal survey. And would you briefly just go over what those four——

Dr. ZURBUCHEN. First of all, Congressman, you're really well informed about how these spacecraft relate to each other and how they're really building on top of each other. You could not imagine a WFIRST without the Hubble being there, kind of doing that kind of work because what we're really doing is looking at the big-data version of the Hubble which is 100 times bigger in terms of many dimensions, but including the data that are coming down for us to mine. And we look at these large-scale structures that are out there and talk about the science overall. What is the universe made out of, you know? Things we call dark just because we don't know what they mean, really.

So the next four that are under consideration, first of all, is a concept called HabEx. You heard, you know, Dr. Mountain talk about LUVOIR. Just like LUVOIR, HabEx is really focused on habitability. So it's focused on looking at, with a slightly different concept but it's looking at emissions that come in atmospheres from planets that would tell us about both the physics of these atmospheres but also whether there's something there that could hint towards the presence of life.

So those are the two that are there, HabEx and LUVOIR. And Lynx is the next generation x-ray surveyor. So there what we're looking at is really the energetic part of the universe, really, in x-rays and gamma rays, looking towards the next generation, looking at these physical processes that—you talked about Chandra or it was talked about, looking at the next generation of physical processes that help us understand how energy actually gets created in some of the weirdest places in the universe.

And then the final one is Origins Space Telescope. It's a system that's following matter around, dust, and elements of the type that we discussed as part of, you know, this unique event there. You know, like how are these transferred around, really. Talk about kind of the origins of these contributions to stars and then what of course could create habitable planets as well.

So those are the three missions looking at a variety of spectral ranges, looking at the variety of centers that actually where these things are rooted.

Mr. BERA. So all of these, in an ideal world, we'd have unlimited resources and all of these missions would provide us vast knowledge and help us. And again, our way of guiding Congress as well as NASA in a purely objective way is to do the Decadal survey, to take this group of scientists and experts, you know, who have much more knowledge than—we're a pretty smart body I think—but who have much more knowledge and expertise than we do and give us guidance. Is that an appropriate, you know, high level——

Dr. ZURBUCHEN. Absolutely, one of the jobs that I don't have is to prioritize which one is the most important one. And you don't want me to have that job. And the simple reason for that is if there's another person sitting in this chair, the whole strategy changes, you know? So we really believe and I'm a strong believer in the wisdom of having a process like the National Academies' insights really driving us because what that creates is constancy of purpose and it creates success, consistency, projects that actually exceed the timeframe of any one of us in any of our respective positions.

Mr. BERA. And would you say the Decadal survey has served this body as well as NASA and the scientific community well?

Dr. ZURBUCHEN. I really do believe so. And you should know before I went to NASA, I was actually actively involved in some of this advisory structure and saw from the inside the kind of high quality of deliberation and the high quality of decision making that's going on there. So I really believe in it and I rely on it every day.

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

Chairman BABIN. I now recognize the gentleman from Alabama, Mr. Brooks.

Mr. BROOKS. Thank you, Mr. Chairman. My questions are directed at Dr. Zurbuchen, but if anyone else wants to chime in, feel free. In September 2017, following a schedule assessment of remaining integration and test activities, NASA announced that it was planning to launch the James Webb Space Telescope between March and June of 2019, a five- to eight-month delay from the previously planned October 2018 launch readiness date.

Given current technical challenges, new information gained from recent deployment tests of the sun shield and remaining work to complete, to what extent is the current expected launch readiness window of March 2019 to June 2019 achievable?

Dr. ZURBUCHEN. At this moment in time, with the information that I have, I believe that it's achievable. But I actually believe what Mr. Young told us about an independent review is exactly what we should be doing. And frankly, I have directed the team to do just that in January. The reason I do it in January and not right now is we're going through fold number two. Remember, what we're really spending time on right now is practicing how to unfold. We want to get this right. And so basically we went through fold number one which took us a lot longer, which to a large extent, together with the propulsion system issue also at the contractor, basically contributed to the majority of the delay. Actually, the only real, you know, delay that was on the outside of the schedule reserve that we had——

Mr. BROOKS. Dr. Zurbuchen, you've already answered my question.

Dr. ZURBUCHEN. Yes.

Mr. BROOKS. I wasn't asking for the causes of delay to date, just what the future looks like.

Dr. ZURBUCHEN. Thank you. I apologize.

Mr. BROOKS. Next, when will the agency announce a specific launch readiness date within this window and how will it determine that this new launch readiness date is realistic?

Dr. ZURBUCHEN. I will submit the exact date for the record because I want to have a schedule from our project office to really make sure that the review is actually, can be done at the right time. I'll submit it for the record. My guess is kind of in January, February timeframe but I don't want to commit to that before I really talk to everybody involved.

Mr. BROOKS. Thank you. Next, the Government Accountability Office testimony states that the Transiting Exoplanet Survey Satellite, also known as TESS, program no longer has cost reserves to cover a delay past March of 2018. What does that mean for the project and how does NASA plan to fund a test launch if it is delayed past March 2018?

Dr. ZURBUCHEN. We expect to solve the problem, through the processes that we have to deal with this kind of unexpected expenditure and basically deal with any delay that will come because it will not be from the fault of the project itself. It will come from the outside.

Mr. BROOKS. In March next year, NASA is planning to launch TESS on the Block 4 version of the SpaceX Falcon 9 rocket. SpaceX has experienced two mishaps in the previous two years with its Falcon 9. In June 2015, a Falcon 9 rocket was destroyed while it was carrying a Dragon cargo spaceship loaded with supplies bound for the International Space Station, and in September 2016 a Falcon 9 exploded on the launch pad while loading fuel for a routine engine test, destroying a commercial satellite. In light of these mishaps, what remains for NASA to certify the Block 4 version of the SpaceX Falcon 9 rocket for the purposes of launching the TESS satellite?

Dr. ZURBUCHEN. I was updated earlier this week that the certification of meetings are scheduled for early next year and basically involved a series of interactions with the contractor and external views of various systems and subsystems. At the completion of that, I really trust the part of our agency that's doing that. I will ask them directly. Is it safe to launch? I'm waiting for that process to come to its conclusion.

Mr. BROOKS. Do you have any concerns or reservations that the Block 4 version of the SpaceX Falcon 9 rocket will not be certified in time for TESS to launch in March of 2018?

Dr. ZURBUCHEN. At this moment in time, I don't have any such concerns.

Mr. BROOKS. All right. Thank you, Mr. Chairman. I yield back the balance of my time.

Chairman BABIN. Yes, sir. Thank you very much. Now, Ms. Johnson has left. I recognize the gentleman from Colorado, Mr. Perlmutter.

Mr. PERLMUTTER. Thank you, Dr. Babin. So I want to start quickly with starshade, because I do have a prop. This is like that, okay? So it helps to—let's go this way. No, that's better. I shouldn't put it in front of my face. That's not a good idea.

But Dr. Zurbuchen, can you tell me about starshade and about the use of both the Academy as well as universities in working with NASA to make sure that starshade provides value and helps us see even more distant objects?

Dr. ZURBUCHEN. The starshade technology together with the coronagraph technology—of course, you're aware that starshade technology was invented in Colorado.

Mr. PERLMUTTER. At the University of Colorado, yes.

Dr. ZURBUCHEN. Exactly.

Mr. PERLMUTTER. Go Buffs.

Dr. ZURBUCHEN. I met the guy. He's an amazing guy, right, because it's more than one invention, of course. It's not the only one. But together with coronagraph technology, starshade technology is a really good way of actually covering up the light of the star to actually blend out that flood of light so we can see the few photons that the faint light that comes from planets. And so basically in many ways it's a very elegant process. It's basically a big shade of the shape that you had there that is perhaps 30 meters or even larger, depending on the geometry, flying 10,000 kilometers ahead of the telescope at a really accurate location and actually use the properties of optics to blend out the star at the telescope to very, very high precision. Coronagraphs are very different. It's much more like a thumb and the camera, like we use when we look at the sun. It's taking light away, internally. Again, a lot of advances are being made there, some advances even today.

So both of these technologies are being developed right now through the technology investments in a variety of places including universities, including within NASA or the organization that Dr. Mountain leads to really look at what the right way is. My prediction is as we go forward in this very new field, that on a timescale of five to ten years, if we have a hearing like this again, there will be even additional technologies that will be proposed, additional ways to solve this really important problem.

Mr. PERLMUTTER. So and I would just encourage you and I imagine Dr. McKee and Dr. Mountain would agree to continue to, you know, partner with the Academy, with the universities as you expand this science.

Now, what I really want to talk about, I'm going to focus, Mr. Young, to you and to Ms. Chaplain. Dr. Mountain mentioned earlier a number with 23 zeros behind it. The number I have in mind isn't that big but it's big. So right now we're dealing with a tax reform bill, the deficit of which is $1.5 trillion. That's what the Budget Office predicts from the House version of that. And it's a number that has 12 zeros after the first so 12 digits.

So just, Ms. Chaplain, help me with the math. You've helped me with other budget issues in the past. And so do you know what the NASA budget is this year?

Ms. CHAPLAIN. The budget request is about $19 billion.

Mr. PERLMUTTER. All right. So let's make it easy. Round it up to 20, okay? $20 billion. That $1.5 trillion hole in the deficit is 75 years' worth of NASA's budget, okay? Let's go to something else. How about — you said we've got a potential or we have a cost overrun on James Webb, initially a $5 billion projected project. Now it's up to $9 billion. How many James Webb telescopes could we build for this budget loss we're going to take of $1.5 trillion? Can you do the math in your head?

Ms. CHAPLAIN. I probably can't do it that quickly, but it's a lot of telescopes.

Mr. PERLMUTTER. Well, let's say the telescope, it booms up to $10 billion in costs. That's 150 of those.

Ms. CHAPLAIN. Yeah.

Mr. PERLMUTTER. Okay? Now, you know what's near and dear to my heart? It's getting our astronauts to Mars, and you and I've had a lot of conversations. Mr. Young, you and I have had a lot of conversations. And at one of our hearings, the number of $200 billion over the next 16, 17 years was suggested by NASA.

So let's do the math on that one. How many times could we go to Mars for this deficit that's coming from this tax bill that the republicans are proposing? I'll do it. It's a rhetorical question but about eight. And that's starting from scratch.

So these numbers are big, and we need to manage these projects the best possible way we can. But on the other hand, when we do things like we're doing, this week and over the next few with this tax bill, we potentially hurt your agencies and a lot of others. And we don't need to inflict wounds on ourselves like that. And with that, I yield back.

Chairman BABIN. Thank you, Mr. Perlmutter. I would remind the crowd out here that there's some of us hoping that we will have enormous growth with this tax bill.

We will now go to the gentleman from Florida, Dr. Dunn.

Mr. DUNN. Thank you very much, Mr. Chairman. I'd like to turn our attention to some of the life sciences that NASA gets involved in. In the '18 appropriations bill as marked up by the Committee, we inserted a provision for NASA to spend at least $10 million on life detection technology. Can you explain briefly, whoever is the right person here, for what are we using for life detection technology? Maybe tell me a little bit about how that compares to the older and what we're developing, briefly, five minutes.

Dr. ZURBUCHEN. Why don't I get started? So part of the life detection technologies are actually the type of technology we already talked about here. So it's basically starshade. It's coronagraph technology as well as other promising approaches that would really help us to actually collect a spectrum of the type that was shown here by Dr. Mountain, like a spectrum that would help us read, if you want, a fingerprint of life elsewhere. And so, it's that kind of technology that we're currently investing in and are committed to doing so in the future.

Mr. DUNN. All right. So life takes some pretty surprisingly different shapes and forms. It can be a little hard for us right here on Earth to decide what is life and what isn't life. I wonder if we are needlessly or unnecessarily limiting the search for the type of lives we might find on an exoplanet.

Dr. ZURBUCHEN. I think it's a really hard question you're asking, what we know about life is what I would always talk of in science language is an $N = 1$. So we have exactly one type of life and many variations thereof.

And so basically what we're doing as scientists—and there's people who are scholars in this, perhaps even at this table—what we're doing is we're going the other way and really asking what does the universe provide us with from in many cases basic principles, from the early universe. But how also how stars work? What are the building blocks and how can life—what would be the principles that we would be using from these building blocks that basically would actually create signatures, in many different scenarios, that are actually different than ours that we could really see.

So it's not so much how exactly what life is but what life does in an atmosphere and so forth.

Mr. DUNN. That's good. So can you explain why it is to the public in general, why are we so fascinated with looking for life? And I don't want a long, I don't want an essay. Have you got a sound bite for me back home?

Dr. MOUNTAIN. For millennia, we've wondered where origins come from. Are we alone? I mean, for four billion years we've looked up at the sky and wondered are we alone? And that loneliness may come to an end if we discover that we are no longer alone. That would change the way we think about biology, change about our civilization. And if we find nothing, think how precious this planet is.

Mr. DUNN. So one of the ways we can spend some of this $10 million is looking for life on Mars with whether manned or unmanned missions we send there. I know we've done that in the past. I know that the answers have been cloudy, murky. But I think there's ways to rather inexpensively clean up those experiments and rerun them with some several Mars landers that are coming right at us.

Let me—because of time, I'm going to skip to the next question. So we've proposed four telescopes here, gentlemen. So why four? Why do we need four different scopes to look at the exoplanets.

Dr. ZURBUCHEN. I just want to make sure. I assume you're talking about telescope studies for the future, the four?

Mr. DUNN. Right, yeah.

Dr. ZURBUCHEN. Yeah. So there, my full expectation is that through the Academy process, prioritization will come. So by us focusing on four, basically what we hope to do is provide a set of options for the Academy to really put the pieces together and actually see what's possible, really translate, if you want, scientific aspiration into some engineering language, and help from that, based on the scientific knowledge we have at that point during the Decadal——

Mr. DUNN. Are you telling me you might cut down to less than four, one, two, three?

Dr. ZURBUCHEN. One will be the first one out of the four. We will not do four at the same time.

Mr. DUNN. Oh, I understand. It just seems funny to be planning for four all at once. So in the few seconds left, why are we launching the James Webb on the Ariane? I understand the cost things. Is it just cost? Why are we using a European missile rather than a good, old-fashioned American rocket?

Dr. ZURBUCHEN. It's a really good question. I already promised to submit that answer for the record and really go through the history of this. I really—I mean, I told you what I know from that.

Mr. DUNN. So, good. Yeah. So I'm a physician. I'd love to get involved with you guys and your life science and your proof of life if you will on whatever planets we land on. And I yield back. Thank you very much.

Chairman BABIN. Yes, sir. Thank you. More Democrats? Let's see, Mr. Higgins from Louisiana for five minutes.

Mr. HIGGINS. Thank you, Mr. Chairman.

Chairman BABIN. Sir.

Mr. HIGGINS. Dr. Mountain, my questions will be directed to you. I'd like to jump right into the next generation of space telescope and space technology as you envision it from your unique perspective, sir.

Over the last several years, microbial life, microorganisms, have been discovered to be quite resilient living in space on the exterior of the hull of the International Space Station and then experiments within minerals and rocks. Do you envision the next generation of search for life throughout the cosmos with our next generation telescopes, do you envision them to be able to measure that spectrum of the wavelengths that we study and search for microbiotic life? Given the fact that the Hubble's been up there for quite some time and future telescopes have been under development for quite some time, and yet it's only recently that we discovered microorganisms on the hull of the International Space Station itself.

Dr. MOUNTAIN. And again, I can refer to my colleague, Dr. Zurbuchen. I mean, it's a very good question. So the issue is that all those microorganisms, whether they be in the space station or in the depths of the Chernobyl reactor or on these deep sea vents, they've all come from one place. It's Earth. This N = 1 problem. And we know that this type of bacteria affected the atmosphere of our Earth roughly a billion years ago and created the oxygen that we now breathe. And so that was the signature that, if we had been on another planet and looked back, we would have seen. The problem is Earths, as I've tried to say, are very faint. We haven't had the power and the capability to look at another Earth-like planet. And I think that the power of this whole idea for NASA's perspective is, it isn't just looking around other stars. NASA wants to go to Europa. It wants to put people on Mars. All of those are potential places where life could have independently come, not just come from our Earth.

Mr. HIGGINS. Specifically speaking of next-generation telescopes, which is trying to stay within the parameters of the purpose of this particular committee and discussion and the search for life by investing massive sums of the people's treasure, we're discussing microorganisms and the search for them. What about silicon-based life, which has been a great deal of scientific discussion about that recently. And do you envision in next-generation telescopes the ability to detect silicon-based life?

Dr. MOUNTAIN. Again, as Dr. Zurbuchen said, we don't yet know what silicon life would look like which is why we believe that the only way to look at this is to analyze the whole spectrum of another Earth-like planet to see things we don't expect and then try and build up models.

What we understand about life is that carbon and water and oxygen are pretty essential. We know, that we don't yet know what silicon life would look like. I don't know if, Thomas, you had anything further. But we haven't yet found a way to recognize what silicon life would be like.

Mr. HIGGINS. Thank you for that answer. In the interest of time, I'd like to jump into what your thoughts are regarding dark matter or dark energy as they relate to current and next-generation telescopes. Dr. Mountain, again, the telescopes we're discussing investing massive amounts of money in will be embedded within the dark energy or dark matter that we call it that because we don't know what it is. Do you envision this next generation of investment to be able to measure that in some way, to give us some answers as a people, be we Democrats, Republicans, or anything in between? We would sure like to know what dark energy and dark matter is.

Dr. MOUNTAIN. As would we scientists. I mean, we are in that fortunate or incredible time where we're using telescopes like the Hubble and other telescopes. We've discovered we haven't understood where the matter comes from. That's dark matter. We haven't understood where the dark energy comes from. That's 75 percent. And that mystery is what's driven missions like WFIRST. We're hoping to be able to measure across the whole sky these very weak effects and give us real insight. What physics are we missing? How is it that we sit in 2017 and we have to say to you we don't understand what 95 percent of the universe is?

Mr. HIGGINS. Exactly. And Mr. Chairman, my time has expired. But should any of the other panel members have input, please, we would like for you to submit your answers in writing regarding the considerations of dark energy. I yield back.

Chairman BABIN. That's very fascinating. Thank you for those questions and answers. Absolutely. I think that's the first time I'd heard of silicon life. I don't want to run into one of those critters any time soon.

Now I'd like to recognize the gentleman from Indiana, Mr. Banks.

Mr. BANKS. Thank you, Mr. Chairman. Harris Corporation located in my district has provided vital technical support for both the James Webb Space Telescope and the Wide-Field Infrared Survey Telescope which we are very proud of, coming from Ft. Wayne, Indiana.

My first question is for you, Dr. Zurbuchen. NASA has put a great deal of time and money into the development of the Webb telescope, and it has the potential to expand on the discoveries of the Hubble telescope. However, since it will be launched into an orbit that makes astronaut repair impossible, it's important that the complicated process of building and launching Webb is done the right way. Do you believe that Webb can be launched and deployed successfully and achieve its objectives?

Dr. ZURBUCHEN. You're talking about—so do I believe that Webb can be launched successfully? Yes, I do.

Mr. BANKS. Okay.

Dr. ZURBUCHEN. So I believe that the work has to be done from all aspects, looked at multiple times. Webb can be done successfully. I'm going to be really nervous during that time, as I always am. Every time I look at a launch now, I'm nervous. But yes . . .

Mr. BANKS. Okay. Good answer. The missions that we're discussing today are very large in scale. The large scale makes these missions expensive and complicated. Is there any consideration, Doctor, at the agency to utilize the growing expertise in small spacecraft to accomplish some of the goals being discussed here today?

Dr. ZURBUCHEN. Absolutely. I mean, so there's a number of approaches that we're looking at, many of them actually on the outside of astrophysics, just because there's many more photons around. The light is much stronger when it comes from the Earth, for example, or from the Sun. And so there's a number of approaches that we're looking at as part of an initiative that I launched when I came to NASA to relook at these systems. And as we go forward and learn how to fly these spacecraft, perhaps they become more relevant for astrophysics on a timescale of 10, 20 years. We don't know. At this moment in time, most of the applications are elsewhere, but even in astrophysics, we're starting to look at them.

Mr. BANKS. So you would agree then that we could reduce mission cost and duration by utilizing small spacecraft?

Dr. ZURBUCHEN. In some of the cases the answer is yes, and in some of the cases like the one with the exoplanets, the bucket size—how big the telescope is is really important because that's the most important driver.

So at this moment in time with the technology we have today anywhere, we don't know how to use small spacecraft for that because it's basically we don't know how to span out a mirror of that size. But you know, I'm sure there's smart people either in your districts or elsewhere that will think about this and really try how to use small spacecraft flying information or otherwise to learn how to do this. I don't know what's going to happen there. Right now we can't.

Mr. BANKS. Good. So it's clear that the projects we're discussing today have the potential for very exciting discoveries. Does NASA have a plan to do outreach to middle and high school students in order to get more young people interested in NASA and space exploration?

Dr. ZURBUCHEN. Absolutely. We're committed to telling our story to all learners of all ages. And I'm personally very excited about middle schools and high schoolers. Of course, I have children that age but also just because I see how much knowledge like this can really impact their careers and their lives. So yes, we're committed. Our programs are doing that now and we commit to doing it in the future together with our partners, many of which are here at the table.

Mr. BANKS. Thank you very much. I yield back.

Chairman BABIN. Yes, sir. Thank you very much. I'd like to now recognize the gentleman from California, Mr. Rohrabacher.

Mr. ROHRABACHER. Thank you very much. I apologize for just coming in now. I was chairing my own subcommittee hearing downstairs, so I apologize. But I will be reading your testimony. I think that the idea of space telescopes and also just the whole idea of astronomy is so important. It's hard for people to come to grips with how important it is for us to know what's going on out there because it sets down—well, anyway, I don't have to explain it to you. You're explaining it to me. But with that said, there's one element that I'd like to talk about, and I don't know. I understand it has not been discussed. And that is I think one of the things that behooves us to work and to have a system that we can identify things as far out as we can go and learn the fundamentals of the universe but also see if there's something out there that could be harmful to us. And we just had—and I don't know if it's still there or if it's gone by—an asteroid that was what, three miles wide, that was just within several million miles of the earth. We need to have a system that we can identify anything coming towards the earth that may well hit the earth at least five to ten years out.

Now Erasevo telescope was almost shut down about ten years ago. They almost closed Erasevo, and Erasevo, it's my understand, is at this point essential to making sure we can identify an object and then track it so we know whether it's actually going to hit the earth or not. But we need to make sure that capability is built into our satellites and our telescopes that we're going to be putting into orbit so that they are also expanding our understanding of the universe but they're also, they are our guards. They are the sentries looking for danger that might be heading in our direction.

Now, is that—I don't know if it's been discussed, but where do you see that in terms of our planning for what type of telescopes and things we will be doing in the future. And I don't know who to ask but whoever would like to comment on that?

Dr. ZURBUCHEN. Congressman, the planetary defense program, which is what you're relating to, is part of our planetary division and is multi-faceted. And like you correctly said, Arecibo is an important part of that because it helps us characterize objects that are really near Earth because we can bounce off, you know, radiation off it and actually look at it at Earth. There's many other assets that we're using—both ground-based and space-based that are there, and actually we're looking as we go forward at even assets that Dr. Mountain and his organization are working with to really in fact provide that kind of information. You of course are aware of that interstellar object that is such a unique first that we found as part of such a survey, a routine survey, at NASA.

Mr. ROHRABACHER. Anyone else?

Dr. MOUNTAIN. Again, just going outside of what NASA does, we are building, you know, the large synoptic survey telescope which will scan the whole sky every three days, and that will provide information that we can provide to NASA as well.

So there is—as you can understand, there is continued coordination. I mean, the asteroid that came in from the outside was actually found by a telescope in Hawaii, ground-based telescope initially and then followed up with NASA's assets including Hubble and other things. And so we are very aware. And of course, the wide-field survey telescope will also have the capability to survey wide areas of the sky. So we're going into this generation of telescopes that can take enormous images of enormous swaths of the sky which is of course what you need to find these rare objects that may be coming our way.

Mr. ROHRABACHER. And Mr. Chairman, I've never talked to a scientist who said, oh, no, we're never going to have a big asteroid hit the world, not one. And not one has ever said, no, we're not—it's impossible that we wouldn't know about it ten years down the road. Well, that's just not—I mean, they all understand that tomorrow, because of what we have not done so far, we could be surprised to find out that most of the earth would be destroyed within a short period of time, within a year or two.

We need to make sure we change that reality. That should be one of our primary goals is that the earth isn't going to be destroyed, for Pete's sakes. And I think that space-based telescopes are going to play a major role in protecting us from that danger, from that ultimate danger. Thank you, Mr. Chairman.

Chairman BABIN. Yes, sir. Thank you. And my Ranking Member over here, Mr. Bera, said he wanted to ask one question.

Mr. BERA. And I'll make it quick because they called votes. Dr. Mountain, you said one to the 23rd? As I wrote this out, that's a lot of potential planets that are out there.

Last year Kepler discovered 1,284, and the total number of exoplanets that we've discovered is about 2,325, 9 of which are potentially in the habitable zone. So part of what we're trying to—the occurrence of life is a rare event, right, and just from my understanding, we're trying to cast a wide net to see as many of these planets as possible. Is that correct, to identify?

Dr. MOUNTAIN. One with 23 zeros is our estimate of all number of stars there are to our universe. Within our galaxy, we believe there's 100 billion, and now from the observations of Kepler just by extrapolation, we believe that most of those have planets. What we can see with our telescopes is only out so far, but we believe that we should search all nearby stars because we believe there are a lot of planets. What we don't know is how many of them have life. But we are going to try with tests, with WFIRST, with all the things that we're doing with our assets on the ground we're going to try and cast that net as widely as we can because life may be extraordinarily rare. We just don't know what that number is. Biologists will argue that even with one to the 23rd, we could be it. I mean, there are good, intellectual arguments from the biology side. We would like to resolve that by going to observe.

Mr. BERA. Thank you.

Chairman BABIN. Fascinating. I also have one, and I think Mr. Rohrabacher's got one as well. We still have about ten minutes. This is for Mr. Young. Would a congressionally mandated cost cap for WFIRST instill cost, schedule and requirements discipline? Would it be satisfactorily done?

Mr. YOUNG. I actually don't think so. I'm not a fan of cost caps.

Chairman BABIN. Okay.

Mr. YOUNG. I think the better solution is what NASA's doing and that is understand the requirements and the cost and risk and technical complexity of the requirements that exist now and adjust those to be what we collectively believe to be affordable and appropriate for WFIRST mission and then, in a rigorous fashion, control them as we implement the program.

Chairman BABIN. Okay. Thank you. Mr. Rohrabacher?

Mr. ROHRABACHER. Yes, and I realize that space telescopes are going to play a really important role in our search for intelligent life somewhere in the universe. We have to cope with the fact that we're trying to find intelligent life here in Washington, DC. right now so—especially on budget issues.

I'd like to ask Dr. Zurbuchen about—what about the NEOCam project and how does that fit in with the space telescopes and the asteroids that I was talking about?

Dr. ZURBUCHEN. So NEOCam is an extended Phase A type of project that we funded out of the Planetary Discovery Program. We're learning through that Phase A what it would take to get to the congressionally mandated numbers of covering, these searches that you talked about earlier within a given number of years. So NEOCam is one of the actual designs that will do so. And there's a couple other things we're looking at with also smaller spacecraft but very much in the spirit of NEOCam. So we're looking at that right now as we go forward and plan.

Mr. ROHRABACHER. But you're saying that that program is under consideration but not decided upon yet?

Dr. ZURBUCHEN. We, at this moment in time, we don't have a budget line or anything at this moment in time that would basically allow us to fund that as part of this. Right now we have our planetary defense budget that you talked about earlier, and it's integral at over $50 million a year. And NEOCam, if you look at the numbers, it's closer to the half-billion type of dollars in round numbers. Of course, it may be 50 million less or more.

Mr. ROHRABACHER. Well, this is just a thought and one major strike. Any type of thing we do to give us some notice or try to knock an asteroid out of the path because we got enough, we have enough warning, would certainly be worth any investment we could make.

Chairman BABIN. Okay. Thank you, Mr. Rohrabacher. We are down to seven minutes. So we need to—I want to thank the witnesses for their very valuable and fascinating testimony and all the members for their questions. I'm sorry, did you have——

Mr.BERA. No, no, I was just going to do the math. How many times does 50 million go into 125?

Chairman BABIN. There's a bunch of smart guys right here. You all come up with that. Anyway, the record will remain open for two weeks for additional comments, and we would appreciate that and written questions by the Members as well.

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

[Whereupon, at 4:19 p.m., the Subcommittee was adjourned.]

Appendix I

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Thomas Zurbuchen

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"NASA's Next Four Large Telescopes"

Dr. Thomas Zurbuchen, Associate Administrator, Science Mission Directorate, NASA

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

1. NASA has funded four large mission concept studies in preparation for the National Academies 2020 astronomy and astrophysics decadal survey. What considerations went into NASA's decision to provide the decadal committee with these studies?

   Answer: The mission concept selection and study process is described in detail in *Planning for the 2020 Decadal Survey: An Astrophysics Division White Paper* (https://science.nasa.gov/astrophysics/2020-decadal-survey-planning).

   Several significant considerations contributed to the decision to provide this set of studies. All of these concepts are based on prioritization by the astrophysics community, and the decision to provide the decadal committee with these studies was endorsed by multiple advisory groups, including the (former) NASA Advisory Committee (NAC) Astrophysics Subcommittee and two committees of the National Academies: the Committee on Astronomy and Astrophysics and the Committee for a Midterm Assessment of the Decadal Survey.

   The starting set of mission concepts were those identified as the community's highest priorities in two reports: the 2010 Decadal Survey and the 2014 NASA Visionary Roadmap, *Enduring Quests, Daring Visions*. The three Astrophysics Program Analysis Groups (PAG) each solicited community input on the set of mission concepts, including regarding whether concepts should be added or removed from the study set, and reported the results to the (former) NASA Advisory Committee (NAC) Astrophysics Subcommittee. The Astrophysics Subcommittee considered the PAG input and delivered a consolidated set of recommendations of concepts to study to NASA. The PAGs unanimously endorsed the four mission concepts identified in the Decadal Survey and the NASA Visionary Roadmap, and the Astrophysics Subcommittee reported out that NASA should study that set.

Please provide an overview of each of the four candidate mission concepts.

Answer: The mission concepts are, in alphabetical order:

- Habitable-Exoplanet Imaging Mission: An observatory designed to directly image planetary systems around Sun-like stars. Its main goal is to directly image Earth-like exoplanets and characterize their atmospheric content;
- Large UV/Optical/IR Surveyor: A large ultraviolet, optical, and infrared observatory with improvements in sensitivity, spectroscopy, high contrast imaging, astrometry, angular resolution and/or wavelength coverage;
- Lynx X-ray Surveyor: X-ray observatory with a large gain in collecting area, angular resolution, and spectroscopic capabilities over previous observatories; and,
- Origins Space Telescope: A far infrared observatory with improvements in sensitivity, spectroscopy, and angular resolution.

How will NASA ensure a level playing field among all four concepts leading up to the decadal survey?

Answer: A level playing field among the concepts will be ensured by, among other means, structuring all of the study teams in the same manner, making the same resources available to each team, subjecting each to the same milestones and deadlines, and ensuring communication between teams. Each team presented its progress to the community at the January 2018 meeting of the American Astronomical Society. Each team will provide an interim report to NASA by March 2018 that will be reviewed to assess progress and provide feedback to each team. Finally, each team will provide a final report to NASA in 2019 that will be submitted to the Decadal Survey Committee. The Astrophysics Division also routinely monitors the progress of each team and provides feedback as necessary to ensure that they will provide suitable input to the Decadal Survey Committee.

2. The development of the Transiting Exoplanet Survey Satellite (TESS) mission is proceeding with an anticipated March 2018 launch date, despite the project's detection of an unexpected drift in focus that will reduce the sensitivity in the telescope's cameras. To determine if the focus drift is stable over long periods of exposure to low temperatures, NASA continues to test a flight spare camera. What will NASA do if a further drift in the focus is found after TESS is launched?

Answer: It is technically incorrect to state that the TESS cameras are "out of focus." TESS is a photometry mission--not an imaging mission--and therefore there is not a single focus value over the field of view. The unexpected shift in focus, noted in the above question, refers to a shift in the location on the focal plane that is in best focus.

Since TESS is a wide field photometry (not imaging) mission, the TESS cameras were never designed to have a sharp focus across the field-of-view. Test data collected on all four flight cameras indicates an optimal focus over as wide a solid angle as was specified in the mission requirements, even with the observed shift in focus. More than one year of ground test data from all four TESS flight cameras indicates that the mission will meet the TESS Level 1 Science Requirements.

The change in focus that was observed in early ground-based testing of the TESS cameras is best described as a "shift in focus" rather than a "drift in focus." After a relatively short time (~1 week) at the selected flight operating temperature, the focus stabilizes and stops drifting. This behavior has been fully verified in months of ground testing of a flight spare camera that is identical to the four flight cameras. If an additional shift should occur for any of the TESS cameras in flight, NASA will follow its standard procedures for assessing both cause and impact, and for determining what actions, if any, are needed to ensure meeting the TESS mission success criteria. One such action could be to incorporate into the TESS data processing pipeline advanced ground-based photometry software—developed since the initiation of the TESS mission—which can track slowly changing image shapes, thus further improving the signal-to-noise ratio for the TESS photometric signals.

The fact that extended flight spare camera testing has revealed no additional long-term focus shift provides high confidence that no additional drift will be observed on orbit. Furthermore, the flight spare camera will continue to be available on the ground to support assessment of any anomalous behavior exhibited by the flight cameras in orbit.

3. Your testimony indicated that the recently announced 5-8 month delay to the James Webb Space Telescope (JWST) October 2018 launch date will not result in the project exceeding the congressionally mandated $8 billion cost cap. Are program level reserves being used to ensure that JWST stays within the cost cap? What level of cost reserves remains at the project and program levels to accommodate any unforeseen issues that may arise in the upcoming integration and testing efforts? In view of the delayed launch, do you envision the contractor receiving any award fee penalty for this current period of performance?

<u>**Answer**</u>: The James Webb Space Telescope program has sufficient reserve funding (a combination of both Goddard Space Flight Center project-held reserves and Headquarters program-held reserves) to cover the launch date change from October 2018 to a March through June 2019 window. Currently, accounting for all encumbrances, liens and threats tracked in the project risk system, the program has 42 percent contingency on the remaining work. The Webb reserve phasing was purposely back loaded to account for our uniquely difficult integration and test program. The Webb contract fee structure has

components for business management, cost, schedule, and technical performance. NASA uses award fee and other tools to manage contractors supporting our missions. During the period covering the launch date change (April 1, 2017 to September 30, 2017) the contractor received no fee for their schedule performance component. Some fee was awarded for solid performance in the technical (i.e., flight hardware) and business management (communication, small business contracting, financial reporting) areas. Some fee was awarded in the cost component area as the contractor did take steps to reduce cost in areas not affected by the delay in schedule.

4. The availability of a 2.4-meter telescope for use on the Wide-Field Infrared Survey Telescope (WFIRST) opened up the possibility of incorporating a coronagraph into the mission design. Can you describe NASA's process for coming to the decision to include the coronagraph on WFIRST?

   Answer: The 2010 Decadal Survey in Astronomy and Astrophysics (*New Worlds, New Horizons in Astronomy and Astrophysics*, National Academies, 2010) recommended that NASA pursue a "new worlds technology development program... to lay the technical and scientific foundations for a future space imaging and spectroscopy mission." When the 2.4 m telescope was made available to NASA, the Agency recognized that one possible way of fulfilling this recommendation would be to add a coronagraph to WFIRST. Accordingly, when NASA chartered a community-based science definition team in 2012 to develop a concept for a 2.4 m version of WFIRST, this team considered the potential benefits of a coronagraph. The team provided a report on in April 2013 that concluded that the coronagraph would be "an exciting extension in [WFIRST's] capability that would not only characterize giant planets around the nearest stars, but also be an important step towards detecting habitable exoEarths." NASA then commissioned the National Academies to assess this mission concept, documented in a March 2014 report entitled *Evaluation of the Implementation of WFIRST/AFTA in the Context of New Worlds, New Horizons in Astronomy and Astrophysics* (National Academies, 2014). This panel found that the coronagraph "satisfies some aspects of the broader exoplanet technology program" recommended by the *New Worlds, New Horizons* report, but noted the risk of including the lower-maturity instrument and therefore recommended that NASA "move aggressively to mature the coronagraph design and develop a credible cost, schedule, performance, and observing program." From July to December 2013, NASA's Exoplanet Exploration Program Office sponsored a working group to identify the optimal candidate coronagraph architecture to be used in future WFIRST studies. The working group, composed of all NASA-supported coronagraph technology developers, reached consensus on the specific architecture.

   The 2019 Budget proposes to terminate the WFIRST mission given its significant cost and higher priorities within NASA. Some funding made available from the proposed termination is redirected towards other priorities of the astrophysics community, including competed astrophysics missions and research.

When did the coronagraph officially become a part of the mission architecture?

Answer: NASA makes no official decisions on the scope of any mission until the project passes Key Decision Point A (KDP-A) and receives approval to formally enter Phase A and begin mission formulation. In conjunction with KDP-A, NASA issues a formulation authorization document (FAD) to define the mission scope. Therefore, the coronagraph officially became a part of the mission architecture when WFIRST passed KDP-A in February 2016. The Science Mission Directorate directed that the coronagraph instrument be included in the mission design as a technology demonstration.

The 2019 Budget proposes to terminate the WFIRST mission given its significant cost and higher priorities within NASA and provides no funding for the mission, including the coronagraph.

What opportunity, if any, did members of the astronomy and astrophysics community have to provide input into that decision?

Answer: As stated above, the Decadal Survey provided the initial prioritized recommendation for coronagraph technology development. A community-based, competitively-selected science definition team developed a concept for the WFIRST mission with the coronagraph, initially as an option. An independent National Academies review assessed the value of the coronagraph and found it to be responsive to the Decadal Survey. A team of technologists, including non-NASA participants, recommended the specific architecture of the coronagraph to be included on WFIRST. The WFIRST mission concept was presented multiple times to community-based advisory committees, including the NASA Advisory Council Astrophysics Subcommittee, the NASA Advisory Council Science Committee, the National Academies' Committee on Astronomy and Astrophysics, and the National Academies' Space Studies Board. In addition, the National Academies' Midterm Assessment of progress on the Decadal Survey (*New Worlds, New Horizons: A Midterm Assessment*, National Academies, 2016) stated that the coronagraph makes WFIRST an "ambitious and powerful facility that will significantly advance the scientific program envisioned by [*the Decadal Survey*]."

5. In your October 2017 memo to the Goddard Space Flight Center directing a design modification study for WFIRST, you directed that the coronagraph be treated as a technology demonstration instrument. Can you explain the costs associated with the coronagraph's treatment as a technology demonstration versus a science instrument?

Answer: By replacing the coronagraph science requirements with less-ambitious technology requirements, NASA is reducing the risk that the cost of the coronagraph will increase during development. As a technology demonstration instrument, the coronagraph will have a simpler design, with fewer operating modes; this will make the instrument easier to build and test without significantly affecting its value as a technology pathfinder. In addition, treating the coronagraph as a technology demonstration instrument allows NASA to (1) eliminate the coronagraph science team; (2) reduce the coronagraph data processing requirements; and (3) eliminate the coronagraph "general observer" program.

What impact would such a designation have on the management of the program?

Answer: The management of the coronagraph instrument has not changed. However, the 2019 Budget proposes to terminate the WFIRST mission given its significant cost and higher priorities within NASA.

Has NASA ever included a technology demonstration on a high priority mission like WFIRST in the past?

Answer: NASA has had technology demonstrations connected with science missions (including missions that have science-related objectives), in some cases with significant visibility. Examples of past and potential future technology demonstrations include the following:

- A synthetic aperture radar mapping instrument on Lunar Reconnaissance Orbiter (LRO), which is a ~$500M-class mission launched in 2009 and described as being "essential for planning NASA's future human and robotic missions to the Moon";
- An optical communications demonstration on the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission, a ~$200M-class mission launched in 2013; and,
- NASA is including an oxygen-production demonstration (Mars Oxygen In-Situ Resource Utilization Experiment or MOXIE). Mars 2020 is a large mission with an estimated cost of approximately $2B.

6. In your October 2017 memo to the Goddard Space Flight Center directing a design modification study for WFIRST, you directed reductions to the coronagraph, the widefield instrument, and the cost of science investigations. Will these reductions result in a reduction in WFIRST's science return? If so, how much?

Answer: The directed reductions to WFIRST were taken with the intent to preserve science capability to the extent possible, while still meeting the cost reduction target.

While the Goddard Space Flight Center is studying modifications to the current WFIRST design, the performance of the Wide Field Instrument is unaltered. However, NASA is reducing science center services for the Wide Field Instrument. Although the scientific potential of the Wide Field Instrument is unaffected, individual scientists may have to do a bit more work to complete their analysis of the data they receive. The net effect on science productivity should be minimal.

The performance of the coronagraph in each mode is not reduced, although the number of modes is reduced, thereby affecting the potential science return. In addition, the changes described in Answer 5 above will make the coronagraph less easily usable for science investigations. Scientists will have to work very closely with the coronagraph instrument team to use coronagraph flight data for science investigations. As a result, there may be a reduction in science investigations. However, NASA's ability to fulfill the WFIRST coronagraph's main purpose, i.e., laying the groundwork for future direct imaging missions, will not be affected.

The 2019 Budget proposes to terminate the WFIRST mission and redirects some existing funding to competed research, including principal-investigator-led astrophysics missions that have a history of providing high science return while training the next generation of scientists and engineers.

How will NASA ensure that the final design of WFIRST is optimized to meet the science goals set forth in the 2010 astronomy and astrophysics decadal survey, which recommended WFIRST as the highest priority large space mission for the 2010-2020 decade?

Answer: The changes above are designed specifically to preserve WFIRST's ability to meet or exceed Decadal Survey science objectives while also meeting Midterm Assessment expectations of cost control to preserve a balanced astrophysics program. The mission science requirements were drafted and/or reviewed by the WFIRST Formulation Science Working Group (FSWG). FSWG members are selected from the community, and are tasked with ensuring that WFIRST will meet or exceed Decadal Survey goals.

The Budget proposes to terminate WFIRST and increase funding for research and principal-investigator-led missions that are high priorities in the Decadal Survey, maintaining balance within a reduced Astrophysics division budget.

7. In your October 2017 memo to the Goddard Space Flight Center directing a design modification study for WFIRST, you indicate that if the Goddard team concludes that WFIRST cannot be developed using the current 2.4-meter architecture within a $3.2 billion budget, you will direct a study of a WFIRST mission design consistent with the 2010 decadal survey. Does that mean that NASA remains open to the possibility of using a 1.5-meter telescope on WFIRST?

   Answer: We are not actively studying a 1.5-meter architecture. As previously stated, the Budget proposes to terminate WFIRST. Some funding made available from the proposed termination is redirected to competed research and missions that are high priorities in the Decadal Survey.

   Would the coronagraph technology demonstration be possible with a 1.5-meter telescope?

   Answer: A 1.5-meter architecture with an unobscured aperture could include a coronagraph technology demonstration, as demonstrated by the 'Exo-C' concept study for a standalone coronagraph mission (https://exoplanets.nasa.gov/exep/studies/probe-scale-stdt/). The smaller 1.5-meter aperture would significantly reduce the coronagraph's potential for scientifically meaningful observations.

   How would the cost and risk of developing a 1.5-meter telescope from scratch compare with moving forward with the donated 2.4-meter telescope?

   Answer: We have not done any design studies for a 1.5-meter WFIRST observatory with a coronagraph, and thus we cannot evaluate the benefits against the risk and cost. A new architecture, built around a new 1.5-meter telescope, would entail different risks than those with a 2.4-meter telescope; the relative magnitude of those risks has not been quantified.

8. The WFIRST Independent External Technical/Management/Cost Review (WIETR) report finds that a Class B risk classification for WFIRST is inconsistent with agency policy for a mission as complex as WFIRST. Does NASA plan to upgrade WFIRST to a Class A risk classification? If not, why not? If so, would there be cost impact and, if so, what would the cost impact be? If not, why not?

   Answer: As previously stated, the Budget proposes to terminate WFIRST. Some funding made available from the proposed termination is redirected to competed research and missions that are high priorities in the Decadal Survey.

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"NASA's Next Four Large Telescopes"

Dr. Thomas Zurbuchen, Associate Administrator, Science Mission Directorate, NASA

Questions submitted by Representative Ed Perlmutter, House Committee on Science, Space, and Technology

1. As discussed during the hearing, the University of Colorado Boulder was instrumental in developing and even holding the patent on the Starshade technology. Private partners like Northrup Grumman and Ball Aerospace have made critical investments in this technology in the past as well. Yet it seems NASA is deviating from past patterns of technology development by concentrating all of its Starshade resources within its own NASA centers instead of including universities and private partners. Can you elaborate on NASA's relationship with universities, like CU Boulder, and private partners in advancing both the development and operation of the Starshade technology going forward?

   Answer: NASA provides opportunities for universities and other private-sector partners to advance exoplanet-related technologies through the Technology Development for Exoplanet Missions (TDEM) component of NASA's solicitation on Strategic Astrophysics Technology (SAT). Since 2009, TDEM proposals from private institutions for starshade technology development have been selected from Northrop Grumman Aerospace Systems, Princeton University, and the University of Colorado Boulder (see https://exoplanets.nasa.gov/exep/technology/TDEM-awards/).

   After five years of starshade technology development, the state-of-the-art had reached a point where individual technologies had been developed through TDEM, and the next step in starshade technology maturation needed to take place at the system level. To that end, NASA established a starshade technology development project at Jet Propulsion Laboratoty (JPL) and incorporated the teams and efforts that were ongoing through TDEM. Work on starshade technology maturation within the system construct has been subcontracted out to partners in both academia and industry. The JPL starshade technology development project continues to solicit and incorporate work performed at partner organizations, and it relies on input and review by a community based assessment committee.

Responses by Ms. Cristina Chaplain

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"NASA's Next Four Large Telescopes"

Ms. Cristina Chaplain, Director, Acquisition and Sourcing Management, U.S. Government Accountability Office

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

1. The WFIRST Independent External Technical/Management/Cost Review (WIETR) report finds that a Class B risk classification for Wide-Field Infrared Survey Telescope (WFIRST) is inconsistent with agency policy for a mission as complex as WFIRST. Can you talk about NASA's previous flagship telescopes and the process NASA used to classify their risk? Why is it important that a mission's risk classification be commensurate with the complexity and scope of the mission? Would you recommend that NASA upgrade WFIRST to a Class A risk classification? What would be the impact of such an upgrade?

   Answer: NASA has established procedures, NPR 8705.4, Risk Classification for NASA Payloads, for assigning a risk classification to projects and programs. The NPR establishes baseline criteria that enable a user to define the risk classification level for NASA payloads on human- or nonhuman-rated launch systems or carrier vehicles and the design and test philosophy and the common assurance practices applicable to each level. When programs and projects establish a risk level early, the project can define and apply the appropriate design and management controls, systems engineering processes, mission assurance requirements, and risk management processes. However, the risk classification may change as the project goes through the iterative formulation process. The NPR provides an approach for defining a hierarchy of risk combinations for NASA payloads by taking into consideration factors such as criticality to the Agency Strategic Plan, national significance, success criteria, magnitude of investment, and other relevant factors. For example, the Hubble Space Telescope and the James Webb Space Telescope are considered Class A missions, while the Mars Reconnaissance Orbiter is considered a Class B mission.

   The WIETR found that the Class B risk classification for the WFIRST mission was not consistent with the NASA policy for strategically important missions with comparable levels of investment and risks. If the WFIRST is reclassified as a Class A, the WIETR estimated it could result in an additional $250 to $300 million in project costs depending on reliability-driven design changes and other mission assurance requirements. As NASA is in the midst of identifying potential ways to reduce the scope of planned activities (called "descopes"), assessing the science impact of those descopes, and developing recommendations for the Astrophysics Division leadership in response to the WIETR, now would be a good time for NASA to reassess if the classification level is still appropriate for the mission.

2. Several of the issues that have arisen during the development of TESS, JWST, and WFIRST stem from problems with NASA's oversight of its contractors, including the focus anomaly with TESS and the thruster valve and scheduling issues with JWST. In your view, would enhanced oversight of NASA contractors have prevented these issues? What can NASA do to improve its oversight of contractor processes and decisions going forward?

   Answer: NASA's telescope and other science projects will always have inherent technical, design, and integration risks because they are complex, specialized, and often push the state of the art in space technology. Our prior reports, however, have found that management and oversight problems—including lax oversight and poor contractor performance—are drivers behind cost and schedule growth. In our recent testimony, we highlighted enhanced oversight of contractors as a lesson learned from NASA acquisitions.[1] When projects improve oversight of contractors, such as through good lines of communication, rigorous monitoring of cost progress, insight into contract workforce levels and a government presence at the contractor facility, it can result in improved project outcomes. For example, in December 2012, we found that the James Webb Space Telescope (JWST) project had taken steps to enhance communications with and oversight of its contractors after experiencing challenges.[2] According to project officials, the increased communication allowed them to better identify and manage project risks by having more visibility into contractors' activities. However, we continue to see instances in our ongoing work that highlight the importance of implementing this lesson learned from JWST.

[1]GAO, *NASA: Preliminary Observations on the Management of Space Telescopes*, GAO-18-277T (Washington, D.C.: Dec. 6, 2017).

[2]GAO, *James Webb Space Telescope: Actions Needed to Improve Cost Estimate and Oversight of Test and Integration*, GAO-13-4 (Washington, D.C.: Dec. 3, 2012).

Responses by Mr. A. Thomas Young

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"NASA's Next Four Large Telescopes"

Mr. A. Thomas Young, Former Director, Goddard Space Flight Center, NASA; Former President and Chief Operating Officer, Martin Marietta Corporation

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

1. In your prepared statement, you note, "*The implementation of a comprehensive, independent requirements review prior to Milestone B followed by a rigorous decision process will mitigate this issue [of requirements creep]. The process being implemented for WFIRST should become standard for all major NASA projects.*" Could you elaborate on that point? Are you referring to all major science projects or do you think the independent review should also be applied to other areas of NASA's mission portfolio such as aeronautics and human exploration?

   Answer: Significant effort is required in the definition of a NASA mission prior to Milestone B, the point at which the approved design, development, integration and test phase begins. During pre-Milestone B activity, science/user teams are involved in more fully determining requirements and project teams are equally involved in definition of the spacecraft, instruments and mission. This is true for science projects, human exploration projects and aeronautics projects. During the pre-Milestone B phase it is not unusual for requirements to be better defined and for additional requirements to be added. It is also not unusual for the scope of the spacecraft, instruments and mission to expand. This can result in a project that is significantly better than the original concept with additional cost and risk that are fully justified and acceptable. Another possibility is that requirements and risk creep results in a project that has unacceptable risk and/or cost. It can certainly be argued that the pre-Milestone B creative activity is important to define the best project consistent with acceptable risk and affordable cost. An independent, external review prior to passing Milestone B can assure that affordable and acceptable requirements, scope and risk are established. For science missions, an assessment can be made as to the responsiveness of the project to the Decadal Survey.

   In summary, a comprehensive, independent, external review prior to Milestone B approval should be implemented for all major NASA projects. The objective of the review is to establish acceptable requirements, scope, risk and cost prior to initiating post-Milestone B activities.

Responses by Dr. Chris McKee

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"NASA's Next Four Large Telescopes"

Dr. Chris McKee, Professor Emeritus of Astronomy, Physics, University of California, Berkeley

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

1. NASA has funded four large mission concept studies in preparation for the National Academies 2020 astronomy and astrophysics decadal survey. What are the benefits, if any, of the decadal survey committee having these studies provided to them at the outset of their deliberations? What, if any, unintended consequences could result from NASA's submission of these studies to the decadal committee? Please provide an overview of each of the four candidate mission concepts.

   Answer: The benefits of having these four studies provided at the outset of the deliberations of the decadal survey are described here. Large space missions are extremely complex and require a great deal of study before their capabilities and costs can be assessed and understood, and before the enabling technology can be brought up to a sufficient technical readiness level (TRL). The 2001 decadal survey had the benefit of the AURA report "HST and Beyond" and a great deal of subsequent analysis to draw on when it decided to make what is now called the James Webb Space Telescope its top recommendation. NASA is proceeding in a more structured way for the upcoming survey: It has solicited mission concepts from the community and, after a selection process that involved members of the community, is providing funding to develop the four most promising concepts and the necessary technology. As a result, the next survey committee will be able to choose among far more developed proposals than previous committees, and the cost and technical risk estimates are expected to be more informative.

   For flagship missions, I do not see any unintended consequences of this long-term advance planning. Flagship missions take many years to execute, and thorough planning, both scientific and technical, is essential before making large investments. Such planning is not suitable for small missions, and the decadal surveys have consistently placed a very high priority on the Explorer program, which enables individual investigators to lead missions that address problems of current interest using the latest available technology.

   I have provided an overview of the four mission concepts under study below, as requested.

First, I will note that NWNH listed three science objectives to be achieved in the decade 2012-2021:

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.

Great progress has been made on each of these objectives, but they are so broad that they will be studied for decades, and as a result the leading questions in the next decadal survey are likely to build on these, with even more exciting scientific explorations recommended. The four mission concepts under development would make significant progress in addressing these objectives. However, it is important to note that these concepts are still under development and are therefore subject to change.

Habitable Exoplanet Imaging Mission (HabEx)

HabEx is a UV/optical/near IR telescope that would be significantly more powerful than Hubble (the current planning is for a 4 meter aperture). It would include a large starshade and a coronagraph to block the light of the host stars and thereby provide very sensitive direct detection of exoplanets and characterization of their atmospheres.

It will search for signs of habitability, such as water, and of biological activity, such as oxygen or ozone. The secondary goal is to use its ultraviolet capability (about 10 times that of Hubble) to enable studies of the intergalactic medium and the life cycles of massive stars.

Large UV/Optical/IR Surveyor (LUVOIR)

LUVOIR will operate in ultraviolet, optical, and near-infrared wavelengths, and will search for habitable exoplanets and biosignatures; characterize exoplanets and their host systems; perform detailed studies of bodies and phenomena within our solar system; investigate galactic structures and evolution on large and fine scales; and study star formation and evolution. The concept team is studying two architectures: one with a 15.1 m primary mirror and the other with a 9.2 m primary mirror. LUVOIR will include 3-4 instruments, depending on the architecture study outcomes: a coronagraph, an imager, a spectrograph, and spectro-polarimeter.

Lynx X-ray Surveyor

Lynx is an X-ray telescope with the collecting area about that of ESA's planned Athena telescope, but with 10 times the angular resolution, 100 times the point source sensitivity, and much higher spectral resolution. The goals of Lynx are to follow the birth, growth, and assembly of black holes across cosmic time; to determine how the evolution of galaxies is largely driven by the violent processes associated with black holes and star formation; to trace how the large amounts of energy and heavier elements generated in these processes lead to the galaxies and larger cosmic structures we see today; and to determine what drives stellar activity and how that activity impacts planet habitability.

Origins Space Telescope (OST)

OST covers the infrared spectrum from 5 to 660 microns and is cooled to 4 K. By studying the spectra of gas and dust in the universe, OST will follow the history of the formation of stars, black holes, galaxies and large-scale structure into the cosmological dark ages; follow water from the interstellar medium to planet-forming disks to planets themselves; and search for biosignatures, including methane, ozone, and carbon dioxide in exoplanetary systems. The team is studying both a 6.5 m and a 9.1 m aperture; with the latter, it would be 3-100 times more sensitive than Spitzer and JWST and 10,000 times more sensitive than Herschel.

Appendix II

Additional Materials for the Record

RESPONSES SUBMITTED BY NASA

Material requested for the record by Chairman Babin during the December 6, 2017 hearing at which Mr. Thomas Zurbuchen testified.

Why was the decision made to launch the $8B JWST on the European Ariane 5 rocket instead of a reliable U.S. launch vehicle? Was cost the only consideration?

Answer:

During the mission concept phase in the late 1990s, European and Canadian scientists and the European Space Agency (ESA) and Canadian Space Agency (CSA) expressed interest in participating in the Webb mission (during this time it was referred to as the Next Generation Space Telescope prior to being re-named the James Webb Space Telescope). The participation was to follow along the lines of other NASA collaborations whereby international partners would contribute hardware on a no-exchange-of-funds basis for a guaranteed fraction of observing time on the facility.

As with the Hubble Space Telescope, ESA and the European science community wanted to utilize roughly 15 percent of the observing time for their science, meaning that their hardware contribution needed to be valued at roughly 15 percent of the NASA cost. To reach that level, ESA committed to provide the Near Infrared Spectrograph, half of the Mid-Infrared Instrument (MIRI), the launch vehicle, some additional hardware and operations personnel at the Space Telescope Science Institute (STScI) located in Baltimore, Maryland.

A launch vehicle contribution presents a relatively small number of simple and well-defined interfaces, and thus is an attractive option from a technical viewpoint and it also is of the right value. ESA offered to build the spacecraft bus, but the complex and large number of technical interfaces, not to mention International Trade in Arms Regulations (ITAR) restrictions, led our Standing Review Board to strenuously recommend that NASA not accept the spacecraft bus as an ESA hardware contribution. Having a significant portion of Europe's Webb contribution come in the form of a launch vehicle avoids these complications.

The Ariane 5 is a proven launcher. As of December 2017, Ariane 5 performed its 82nd consecutive successful mission since 2003. Its most recent launch, on January 25, 2018, had an anomaly during ascent. Initial investigations from Arianespace reveal a trajectory deviation following launch. NASA is confident the direct cause of the anomaly will be identified and corrected for the vehicle to launch Webb successfully. ESA invited NASA participation in its review of the January Ariane launch deviation so that the agency has additional, direct insight to the event. Independent of the most recent launch, both ESA and NASA had instituted additional reviews and insight opportunities into preparations for the launch to ensure success because of the considerable cost and complexity of Webb. This increased insight and collaboration has enabled Webb to tailor its hardware and testing program specifically for launch on the Ariane 5. Our as-built and tested structures are precisely tuned to the vibration and acoustic environments of the Ariane 5.

Material requested for the record by Chairman Babin during the December 6, 2017 hearing at which Mr. Thomas Zurbuchen testified.

What are the risks associated with the transporting of JWST to the European launch site located in South American French Guiana?

Answer:

The primary risk associated with shipping the telescope is the weather and sea conditions along the route. NASA has, and will continue to work with the USTRANSCOMM (DoD) to assess threats both natural (seas, weather) and otherwise leading up to and during the shipping. ESA uses this very same ship to send components to Kourou, so it has a well-established process. NASA has already sent instruments on two separate ship voyages to gather data on the accelerations and environments that the shipping container will experience in route. All measurements indicate that the shipping container provides adequate protection against contamination and that accelerations are within safe limits.

Material requested for the record by Representative Brooks during the December 6, 2017 hearing at which Mr. Thomas Zurbuchen testified.

When will the agency announce a specific launch readiness date within this window and how will it determine that this new launch readiness date is realistic?

Answer:

NASA will conduct a schedule review in the coming weeks. The results of the schedule review, along with outcomes from this spring's environmental testing of the spacecraft element, will inform the selection of a launch readiness date. The Webb launch readiness date will be announced after those activities are complete.

Material requested for the record by Representative Dunn during the December 6, 2017 hearing at which Mr. Thomas Zurbuchen testified.

Why are we launching the James Webb on the Ariane? Is it just cost? Why are we using a European missile rather than a good, old-fashioned American rocket?

Answer:

During the mission concept phase in the late 1990s, European and Canadian scientists and the European Space Agency (ESA) and Canadian Space Agency (CSA) expressed interest in participating in the Webb mission (during this time it was referred to as the Next Generation Space Telescope prior to being re-named the James Webb Space Telescope). The participation was to follow along the lines of other NASA collaborations whereby international partners would contribute hardware on a no-exchange-of-funds basis for a guaranteed fraction of observing time on the facility.

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