Statement of

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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.

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.

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.

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.