**Statement of**

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**before the**

**U.S. House of Representatives**

**Committee on Science, Space and Technology**

**Subcommittee on Space and**

**Subcommittee on Research and Technology**

**July 12, 2016**

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

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

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

## WHY ASTRONOMY MATTERS

Throughout history, astronomy has provided fundamental contributions to science and insights about the nature of our Universe. Over several centuries, our view of the Universe and our place in it has changed dramatically. Copernicus revolutionized our view, in the early 1500's, when he proposed that the Sun and not the Earth was the center of the Universe. Kepler demonstrated how planets in our solar system orbit the Sun. This work provided part of the foundation for Isaac Newton's theory of universal gravitation.

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

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

## THE BIG QUESTIONS FOR ASTRONOMY

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

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

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

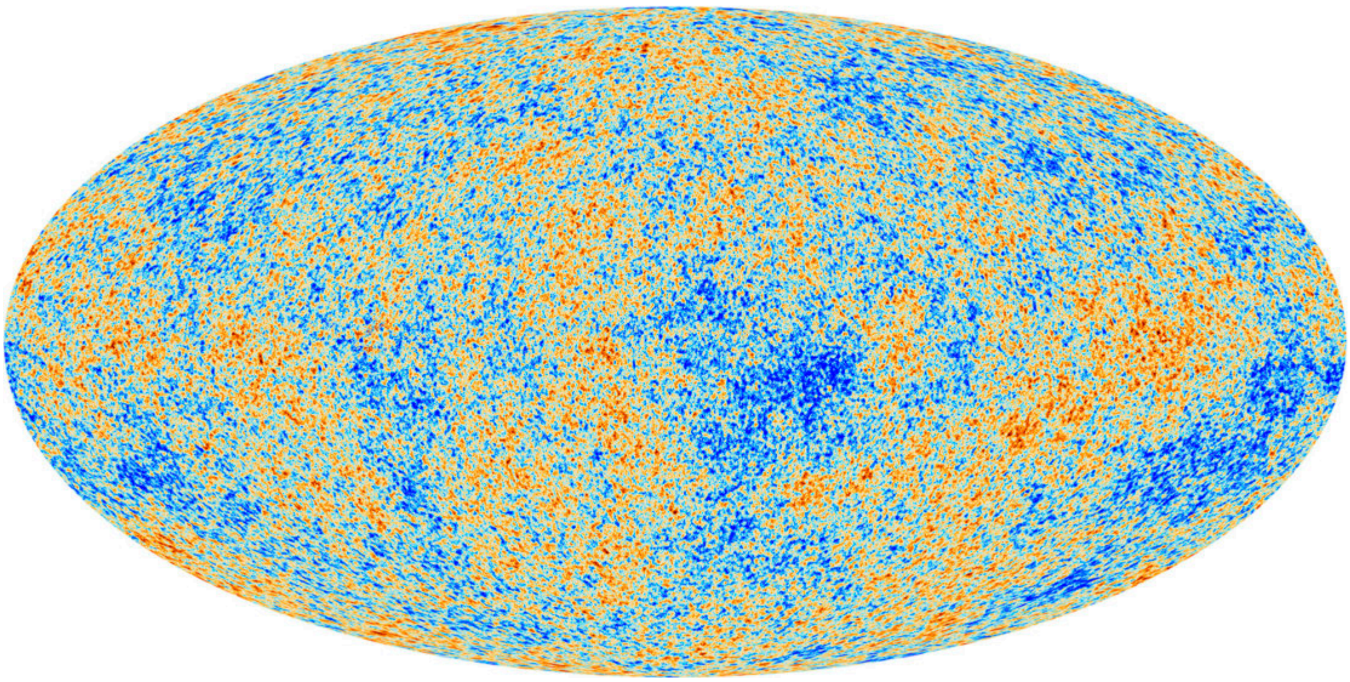

Figure 1. The small scale anisotropies of the cosmic microwave background (CMB) as observed by the Planck satellite. The CMB is a snapshot of the oldest light in our Universe, imprinted on the sky when the Universe was just 380,000 years old. The observed fluctuations reflect tiny temperature fluctuations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

**RECENT DISCOVERIES IN ASTRONOMY**

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

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

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

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

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

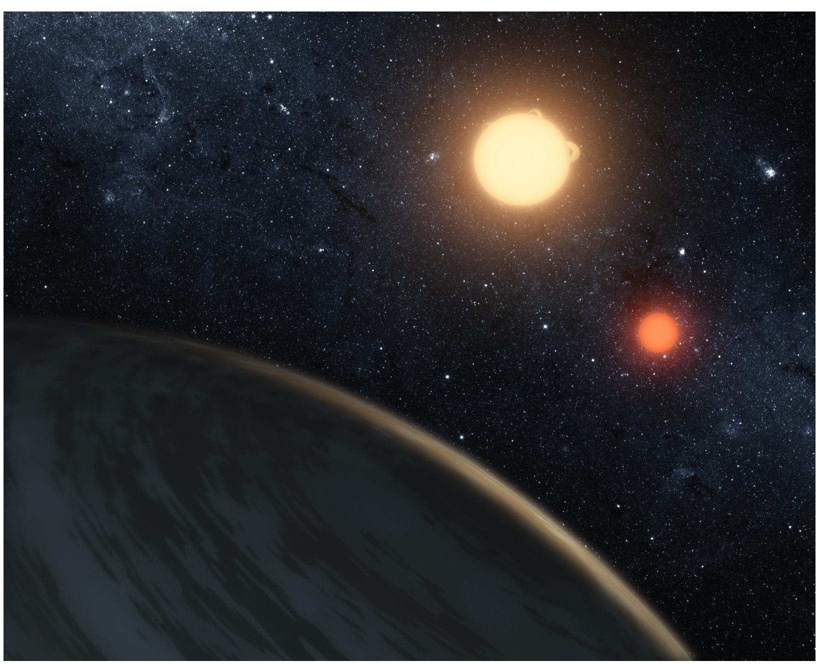

Figure 2. This artist's concept illustrates Kepler-16b,aka Tatooine, the first planet known to definitively orbit two stars - what's called a circumbinary planet. The planet, which can be seen in the foreground, was discovered by NASA's Kepler mission. Credits: NASA/JPL-Caltech/T. Pyle

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

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

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

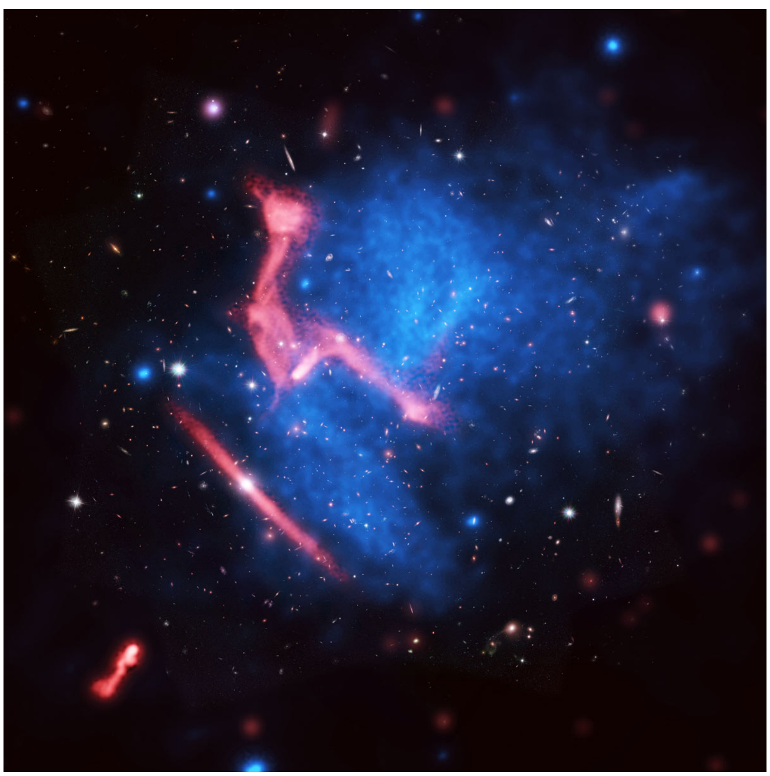

Fig 3. The colliding galaxy cluster MACS J0717+3745, more than 5 billion light-years from Earth, is one of the most massive galaxy clusters known in the Universe. The colliding subclusters produce shocks and accelerate particles to very high energies. The massive cluster also provides a "cosmic" lens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

**STELLAR MASS BLACK HOLES AND FIRST DETECTION OF GRAVITATIONAL WAVES**

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

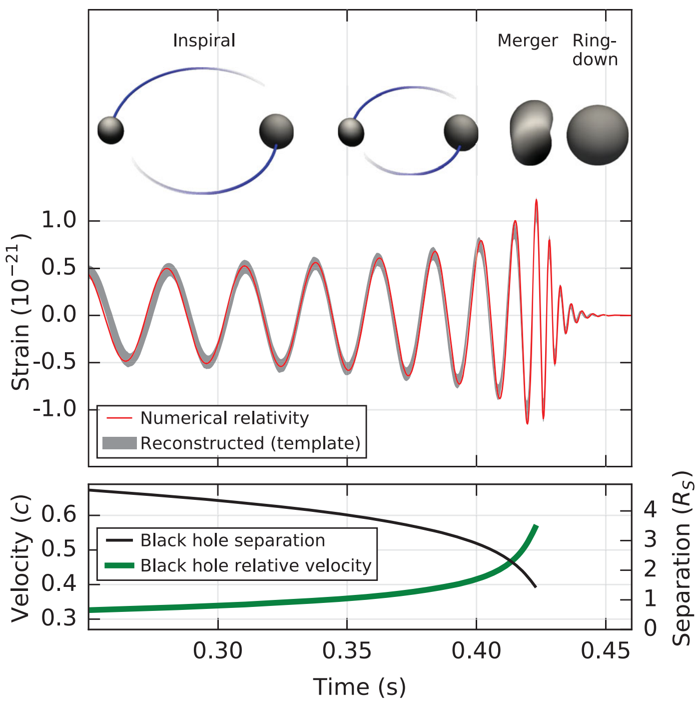


Fig. 4. Top: Estimated gravitational-wave strain amplitude from the first gravitational wave detected by LIGO - GW150914. The inset images show numerical relativity models of the black hole horizons as the black holes coalesce. Bottom: The Keplerian effective black hole separation in units of Schwarzschild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

**LOOKING BACK IN TIME**

The current ground and space-based observatories have brought us closer to understanding how the Universe formed, and how it evolved over the last 13.8 billion years. When we look at very distant galaxies, we are observing them as they were when the light we see now was emitted. We are essentially being allowed to look back in time to see galaxies when they were young. Quoting from my colleague Alan Dressler, "Astronomers have an advantage over other historians: they can observe history directly – if not their own, at least someone else's". With Spitzer, Hubble, WISE, and large ground-based telescopes, we are able to observe very distant galaxies at a time when the Universe was less than a billion years old. Currently the most distant galaxy known has a confirmed redshift of 7.7, which corresponds to a time when the age of the Universe was only 0.7 billion years. Many of the galaxies found in the early Universe are irregular in shape and much smaller than our Milky Way. With the launch of the James Webb Space Telescope in 2018, we will be capable of observing the first stars, likely formed when the Universe was only a few hundred million years old, only about 3% of our Universe's present age.

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

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

## UNDERSTANDING OBSERVATIONS BETTER THROUGH SIMULATIONS

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

## PLANNNING FOR THE FUTURE – the Decadal Surveys

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

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

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

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

## INTERNATIONAL PARTNERSHIPS

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

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

**ASTRONOMY AS A GATEWAY SCIENCE - STEM Education and Outreach**

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

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

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

**TECHNOLOGY and SPINOFFS**

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

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

My own field of research is X-ray observations of distant galaxies and clusters of galaxies. Riccardo Giacconi was one of my mentors and was the primary founder for the field of X-ray astronomy for which he received both the Nobel Prize for physics and the National Medal of Science. Giacconi's early work was done at American Science and Engineering in Cambridge, MA. This work provided the foundation for AS&E's technology for counter-terrorism and security applications. Every visitor to the National Air and Space Museum still puts their backpacks and pocketbooks through security scanners with AS&E labels on their sides.

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

## CONCLUDING REMARKS

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

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

Our community is deeply concerned about the impact of ongoing flat research budgets at NSF. While managers at NSF are striving to maintain programmatic balance—always the overarching priority of our decadal surveys—in the face of flat budgets, they have run out of options and something will have to give. History teaches us that the "something" will likely be individual research grants. So i is a very positive step that the current NSF reauthorization in the Senate includes four percent increases for NSF through FY 2018. I hope that Congress will ultimately authorize a longer, sustained growth trajectory for NSF.

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

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

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