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Statement of

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Mr. Chairman and Members of the Committee, thank you for the opportunity to appear today at this notable event celebrating the 50th Anniversary of the National Aeronautics and Space Administration (NASA). Exploration is a human imperative; indeed our efforts to investigate and understand the unknown form the foundation on which our nation was built. Our citizens are descended from those who dared to abandon familiar confines and safe harbors for the uncertain chance of a better life. Indeed, the impetus to explore is coded into our DNA. It certainly is for me. I spent endless evenings during my youth freezing in my backyard viewing the night sky with my homemade telescope. Now I explore the solar system from an office overlooking the Charles River where it is also my privilege to train the next generation of young people who will innovate, discover and lead our nation forward in scientific and technological endeavors. Today, I will address NASA's accomplishments in space and Earth sciences from both a scientific and educational perspective, and with an eye towards an even brighter future.

Accomplishments in Space and Earth Sciences

The list of scientific achievements in the space and Earth sciences that can be traced to NASA in the fifty years since its inception is as extensive as it is impressive, and my review must necessarily be illustrative rather than comprehensive. I apologize in advance for the numerous discoveries that I omit for brevity.

Beginning "next door," the Apollo Program revealed that the Moon, and by extension the rest of the solar system, is ancient, having formed over 4.5 billion years ago. Moon rocks, and later meteorites, analyzed in state-of-the-art geochemical laboratories provided the evidence for that discovery. The early solar system was a violent place; many planetary surfaces are saturated with impact craters that formed primarily due to impacts from debris left over from the disk of dust and gas encircling the Sun that condensed to form the planets.

Impacts, though they are low-probability events today, played a crucial role in shaping the planets. The Moon itself probably formed from the impact of a Mars-sized impactor into the Earth. An impactor larger than Pluto likely produced the low-elevation northern hemisphere of Mars, believed by many to be the former site of an ancient ocean. Another massive impactor may have stripped off much of the mantle of Mercury leaving a core that is three-quarters the size of the planet.

NASA missions revealed other important processes that shaped the terrestrial planets. The Magellan mission to Venus penetrated the thick atmosphere of that planet to show most of the surface was covered almost simultaneously (in a geologic sense) by volcanic flows about 600 million years ago. The surface also shows evidence of intense fracturing, rifting and folding that is the manifestation of dynamic forces within Venus' interior, the kinds of forces that produce earthquakes on our home planet. The closest planet to the Sun, Mercury, which was first imaged by flybys of the Mariner 10 spacecraft and more recently by MESSENGER, shows remarkably diverse evidence for wrinkling of the surface suggesting the planet cooled and contracted, and odd volcanic features including a fascinating spider-shaped volcanic center.

The advance in our understanding of the planet Mars over the past decade can be counted among NASA's greatest successes, both from a scientific and technological perspective. Landing on Mars is arguably the most difficult thing we do in the robotic space program. The remarkable descent vehicles that execute precisely timed events that collectively comprise the entry-descent and landing sequence are confounded by the planet's turbulent atmosphere and rocky surface. The combination of observations from orbiters, landers and rovers has established firmly the evidence for a more clement early climate and a watery past. The discovery of vast reservoirs or polar surface ice and subsurface ice has removed a major impediment to future human exploration of this most Earth-like of terrestrial planets.

NASA missions have revealed the nature of the solar system's small bodies – asteroids, comets, Kuiper Belt Objects. In addition to contributing toward the inventory and dynamics of these remanents of planet formation, NASA spacecraft have landed on an asteroid, (purposely) impacted a comet, and flown through a comet tail to sample the primitive icy materials. In addition, the New Horizons spacecraft is now enroute to the most prominent Kuiper Belt Object – Pluto.

Other discoveries in the outer solar system have defied the imagination. The Pioneer, Voyager, Galileo, and most recently, Cassini missions have revealed the giant planets' massive cloud systems and their complex dynamics, as well as the prevalence of ring systems whose study has informed modeling of the formation of the solar system. The diversity of outer satellites is remarkable: active volcanism on Jupiter's moon, Io, and a likely subsurface ocean beneath Europa. Icy geysers on Neptune's moon Triton and Saturn's tiny, frozen moon Enceladus imply the presence of underground pockets of liquid water laced with organic molecules. In collaboration with European colleagues, Cassini-Huygens identified organic-rich rivers and lakes and atmospheric hazes on Saturn's active moon, Titan, the only other known planetary body with a nitrogen atmosphere like Earth's.

And the remarkably resilient Voyager 1 spacecraft continues its three-plus decade journey of discovery, observing the farthest limits of the solar system.

So many of NASA's greatest discoveries have been serendipitous. Perhaps the most striking example comes from NASA's astrobiology program. Originally conceived to address the plausibility of life beyond Earth, the program encouraged study the of the range of environmental conditions under which Earth-like life can survive. This program has been spectacularly successful in fueling progress in the field of life in extreme environments, and the research has also been instrumental in advancing our understanding the conditions under which life may have developed and proliferated on the early Earth.

NASA's contributions toward understanding the state and workings of our Earth has a tremendously rich history. The most innovative approaches used in remote satellite observation were developed by NASA or by the scientific and technological community under the auspices of NASA support. Satellites and analysis tools originally conceived and built by NASA are commonly distributed to other, more operational, government agencies, such as the National Oceanic and Atmospheric Association of the Department of Commerce, and the U.S. Geological Survey under the Department of the Interior. Among numerous accomplishments NASA can claim credit for the first measurements of the steady but miniscule motions of the Earth's tectonic plates, characterization of the ozone hole, the three-dimensional structure of hurricanes, the general circulation of the oceans, biological ocean productivity, rainfall patterns in the tropics, and the global wind pattern over the oceans and its relationship to wave distribution and height. Efforts are ongoing to study changes on the Earth on decadal time scales – sea level rise, the surface ice volume, and measurement of changes in water reservoirs.

NASA's studies of the Earth's plasma environment have been central in understanding the phenomenon of "space weather", as well as the magnetic character of the Sun and the nature of the solar atmosphere.

The contribution of NASA to scientific knowledge is truly impressive. The respected publication *Science News* indicates that 5-10% of all scientific discoveries, worldwide, over the past decade, can be traced to NASA. I routinely tell my students that there has never been a better time to be a space or Earth scientist. The web page of NASA's Science Mission Directorate lists nearly a hundred missions currently operating or in development studying the Earth, our solar system, the heliosphere and beyond. With this record of scientific achievement is it any surprise that the rest of the world aspires to be like us? Nearly forty years after the first humans walked on the Moon, nearly every space-faring nation is either actively executing or planning missions to the Moon. Many of those same nations are planning missions to Mars. Can the rest of the solar system be far behind?

Most Exciting Possibilities and Opportunities for New Scientific Discovery

About a week before our team's laser altimeter experiment arrived at Mars I received a call from a member of the press asking me what I was going to discover. I explained that if I knew I could have saved others and myself the trouble of designing and building the instruments and spacecraft. But while I didn't know what I would discover I knew without question that our experiment was worth doing. Anytime that one has gone to a place no one has been before, or looked at a place visited earlier with a novel new sensor, discovery has been assured. There has never been an exception. Even high expectations are often surpassed by large measure. The beauty and complexity of the natural world exceeds our imagination. Beyond that realization, however, there are some simple rules that can guide a vibrant program.

First, one doesn't know where the next significant discovery will arise, so a balanced scientific program is essential. Destinations should be chosen on the basis of decadal studies and strategic plans forged by community input. Peer review must continue to be employed to identify the most compelling science within the context of tractable plans for implementation. A mix of smaller missions with focused objectives should be combined with flagship missions with ambitious objectives or challenging destinations.

The Moon is for a fascinating target for future scientific study. The Apollo Program provided a treasure trove of information in the lunar samples that are still being analyzed today, but they sample only a half-dozen locations. If one visited only a half-dozen locations in the United States how well would one understand our country? With numerous missions enroute to, or planned for the Moon, including the Gravity Recovery and Interior Laboratory (GRAIL) mission which I am privileged to lead, the next decade or more will represent a golden age of lunar exploration. I feel about the Moon the same way that I felt more than a decade ago in advance of a suite of orbiter, lander and roving missions that redefined our view of the planet Mars. As the most accessible example of a primordial planetary body, future study of the Moon will provide transformative advances in our understanding of the early evolution of all terrestrial planets.

Returning samples from Mars -- from sedimentary, volcanic and volatile environments with well-studied geological context -- should be the highest priority in future Mars exploration. Such samples will match the value of moon rocks in deciphering that planet's early and present environment.

The outer solar system offers numerous thrilling destinations for future study and I see the next steps motivated in large measure by information returned from the Cassini and Galileo missions. A number of the icy moons (Europa and Ganymede of Jupiter and Enceladus and Titan of Saturn) are characterized by the presence of liquid water and/or organic volatiles and they hold the possibility of harboring life. The choice of nearest-term targets should be driven by peer review analysis that indicates that discoveries considerably beyond the current state of the art are possible within the context of current technology and affordable technology development.

Reconnaissance and/or sampling of small bodies will be of great value. From a practical standpoint a detailed study of the internal structure and constitution of an asteroid would be informative regarding the challenges that would be faced by an near-Earth asteroid that might one day be recognized to be a potential Earth impactor.

Likewise there are numerous challenging questions about workings of Earth that are appropriate for study by NASA. There seems to be a spectrum of opinion both within and outside the agency as to how much NASA should be involved in Earth science. As head of a pre-eminent Earth Science Department with a view on the most challenging questions in contemporary Earth and atmospheric science and oceanography, I have a strong opinion on this topic. The Earth is a complex, dynamic, system of systems that requires detailed *in situ* study combined with precise global views over time to unravel its workings. From the point of view of remote observation, no other agency is capable of developing the kind of state-of-the-art sensors and observation strategies that only NASA can provide. NASA simply must play a role in the essential mission of understanding our Earth.

Science goals of high merit in solid Earth, atmospheric, oceanic, hydrologic and cryospheric science have been prioritized in a recent decadal study that forms the plan for moving ahead. The questions are of both purely scientific interest and practical regard, the latter associated with natural hazards and climate change. What is clear in both cases is that collection and analysis of high-quality data of global extent, with repeated observations over time, is essential if we are to understand the state and future of our Earth.

One of the most astounding discoveries in space science over the past couple of decades has been the detection of planets around other stars, also known as extrasolar planets. Over three hundred of these objects are known now and after years of unsuccessful searching their rate of discovery is now rapid. Detection of these objects is mostly indirect, by tiny perturbations of parent stars and dimming of such stars as the planets pass in front of them. But most recently spectra have been measured and the first atmosphere detected. Most of these objects are giant planets very close to their stars, inside the orbit of Mercury by analogy with our own solar system. But detection of "super-Earths", large terrestrial-like planets, is now becoming a reality. A very high-priority challenge in coming decade is to image Earth-sized planets in the so-called "habitable zone" of their stars, that is, where conditions are favorable for Earth-like life. Large space-based deployable optics and the realization of coordinated sensor arrays are key in realizing this exciting scientific objective.

Judicious investment in new technology will be required to take future scientific giant steps. Technological hurdles tackled early, in advance of mission selection, are the best prevention against cost overrun. A prime example of an enabling new technology is the transition from radio to optical communication to take advantage of much increased data rates enabled by the shorter wavelength of light compared to radio waves. Such a system would be required to realize, for example, near-real time streaming video from the surfaces of other planets. The challenge is how to balance new investment with transformative possibilities with maintaining current facilities and continuing operations that have excellent return.

There is much worthwhile science to be done, but NASA cannot afford to do all of it. Prioritization needs to occur in order to move productively forward. Strategic plans must be developed and implemented, with flexibility to respond to discovery or enabling technology advances. A stable funding profile in space and Earth science is essential to progress. Here I acknowledge and in fact applaud the efforts of the Committee for their strong support of NASA science, exemplified by the most recent NASA bill passed by the House.

Inspiring the Next Generation

In 2003 I had the privilege of serving on the Presidential Commission to develop an implementation plan for the Vision for Space Exploration. One of the most eye-opening experiences of my participation on the Commission was reading the commentary of the general public with regard to space science and exploration, and traveling around the country talking to citizens about space. A remarkable outcome of the Apollo Program is how many children of the Apollo era grew up to study science or engineering because they were thrilled and amazed by the quest to reach the Moon. By and large, only a small percentage of these folks (present company on the committee excluded) grew up to participate directly in the space program. Most of them grew up to pursue other disciplines, and today they are computer engineers, telecom engineers, chemists, physicists, etc. Last week on telling a friend that I would be testifying about the accomplishments of NASA, he told me: "Talk about inspiration. There's no doubt that I became a scientist because of my fascination with the space program when I was a kid." This individual is a molecular biologist who was elected this year to the National Academy of Sciences.

This anecdote highlights a key attribute of the space program, namely, its ability to inspire young people to pursue scientific and technical careers. But it is important to mention that the evidence is anecdotal and difficult to quantify. We don't know how many people inspired by the space program pursued a math, science or technology degree who wouldn't have done so any way. Many of the young people now fascinated with the latest discovery from Saturn or in driving Mars rovers have the potential to take on the greatest societal challenges in energy, the environment, and health care to name a few. Students inspired to pursue scientific careers must then be trained. We do know that college-level students are making use of NASA data to assist in their training for a range of professional careers. In my own university students interested in energy flock to me and other NASA-funded researchers to obtain experience in remote sensing, chemical analysis, robotics, and instrument design to name but a few. A stable funding base to universities, all awarded via peer review, is crucial for training the scientific and technical professionals of the future.

Attracting the best technical and scientific workforce will require access to the entire pool of top talent. We must work tirelessly to attract and engage all students with mathematical and scientific aptitude independent of gender, race, etc. We must provide opportunities to top scholars from the international community to participate in the American Earth and space science endeavor, recognizing their potential for contributing to our technical preeminence.

Because NASA is the agency of discovery, its potential for outreach is extraordinary. Few can fail to appreciate the stark beauty of an alien landscape revealed for the first time, or the difficulty of designing a spacecraft to fly close to the Sun. But there is no perfect measure of engagement. In outreach programs it is possible to measure web hits or museum attendance, both useful indicators, but far more difficult to measure when a child has been sufficiently inspired to take the harder math course or to consider science for a career for the first time. We must trust in the power of scientific discovery to motivate in its own right.

NASA does not have the scope, mandate or resources to solve all education problems in our country. But the agency most assuredly has the ability to nudge those with the "right stuff" in the direction of careers in science and technology. There is nothing like hands on experience on a difficult problem that better brings out the joy of learning. There must be room for creative, hands-on programs that complement broader programs with wide reach. On my GRAIL mission America's First Woman in Space, Sally Ride, and I have teamed to offer an innovative student project. Leveraged by an ongoing program called EarthKAM that Sally and her educator colleagues currently operate on the International Space Station, our MoonKAM program will place up to five cameras on each of two spacecraft sent to orbit the Moon. These cameras will be used entirely for educational and public outreach. By decoupling the experiment from the formal science objectives of the mission and making everything about the experiment "best effort" rather than measurable success, it is possible to implement the program in an affordable manner and on a non-interference basis. Middle school students across the United States will have the opportunity to study the Moon and propose targets to image, and selected images will be sequenced by a team of competitively selected undergraduate students supervised by trained professionals. Our collective conviction about the inspirational value of a space-based imaging experiment solely dedicated to outreach is great. We are absolutely certain that the experience will extend the NASA tradition of changing lives and motivating future careers.

In summary, NASA is the federal agency where dreams reside. Its can-do attitude and propensity toward taking on tasks, in President Kennedy's words, "because they are hard" exemplifies so much of what is great about our country. Other nations emulate us, follow our lead, and partner with us in peaceful exploration of the solar system and beyond. I sometimes wonder how I managed to be so fortunate to be born at a time that allowed me the opportunity to pursue my penchant for scientific discovery in the solar system. I do believe in a bright future for NASA, one in which young people with similar inclination will feel as I do fifty years from now at NASA's centennial celebration.

I genuinely appreciate the forum that the Committee has provided to recognize the achievements of NASA, and I look forward to responding to your questions.