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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; our efforts to investigate and understand the unknown form the foundation upon 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 and to discover 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 investigate, innovate, 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 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 planetary body 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. NASA's first planetary mission, Mariner 2, flew past Venus during December of 1962, providing the first direct evidence for the high surface temperatures and the intense greenhouse effects produced by the massive carbon dioxide atmosphere. The subsequent Pioneer Venus and later Magellan missions penetrated the thick atmosphere of that planet to show that most of the surface was covered almost simultaneously (in a geologic sense) by volcanic flows nearly 600 million years ago. Observations also showed 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 during the 1970's and more recently by the MESSENGER spacecraft, shows remarkably diverse evidence for wrinkling of the surface suggesting the planet cooled and contracted, odd and diverse volcanic features, and complex coupling of the planet's plasma environment to the solar wind.

The advance in our understanding of the planet Mars over the past decade can be counted among NASA's greatest successes, from both scientific and technological perspectives. Landing on Mars is arguably the most difficult thing we do in the robotic space program. The remarkable spacecraft 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 that Mars had a more clement early climate and a watery past. The discovery of vast reservoirs of 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 building blocks – asteroids, comets, and Kuiper Belt Objects. In addition to contributing toward the inventory and dynamics of these remnants 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. NASA's New Horizons spacecraft is now en route to the most prominent Kuiper Belt Object – Pluto. And NASA supported research has contributed to the discovery of many other distant Kuiper Belt objects beyond the orbit of Neptune, including one even larger than Pluto, which helped fuel the recent debate regarding the re-definition of the term "planet". NASA measurements have also led to the discovery of material formed outside the solar system and prior to the formation of our Sun.

Other discoveries in the outer solar system, collected over three decades, have defied the imagination. The Pioneer 10 and 11 , Voyager 1 and 2, 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 its astrobiology program. Originally conceived to address the plausibility of life beyond Earth, the program encouraged study 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.

While we rightly consider NASA to be the space agency, its history of discovery in Earth science is, ironically, out of this world. NASA's first satellite, Explorer 1, led to the discovery of the van Allen radiation belts, which encircle the Earth. More recently, 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.

Two years after the launch of America's first satellite, Explorer 1, in 1958, NASA launched the world's first weather satellite, TIROS-1 in 1960. Since that time, the most innovative approaches used in remote satellite observation for scientific purposes have been developed by NASA or by the scientific 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 Administration of the Department of Commerce, and the U.S. Geological Survey under the Department of the Interior. NASA satellites have continued to contribute to our understanding of the Earth's weather and climate. Recent improvements in measurements of surface and atmospheric temperatures and humidity by the infrared spectrometer on the Aqua mission, combined with more advanced models have recently increased the range of reliable weather forecasts by 6 hours, the largest advance enabled by a single instrument in over a decade. Additional measurements by other NASA missions are revolutionizing our understanding of the three-dimensional structure of hurricanes, as well as the genesis, evolution, tracking, and prediction of these fierce storms.

NASA satellites have also contributed to our understanding of the composition of Earth's atmosphere. The Total Ozone Mapping Spectrometer instruments flown on NASA satellites in the 1970's and 1980's led to the discovery of the ozone hole and provided the first quantitative maps of its spatial extent and depth. More recently, other NASA satellites have provided important insights into to mechanisms responsible for producing and destroying ozone, information vital for our ability to predict the recovery of the ozone hole and other future ozone trends. Within the next few months NASA will launch the Orbiting Carbon Observatory which will measure and monitor carbon in its many forms in the atmosphere, including the powerful greenhouse gas carbon dioxide.

Other NASA spacecraft have mapped ocean circulation patterns, biological ocean productivity, wind patterns over the oceans and their relationship to wave distribution and height, and the global distribution of land vegetation species, and their state of health and change over time. Efforts are ongoing to study changes on the Earth on decadal time scales – sea level rise, the surface ice volume, changes in water reservoirs including rivers, lakes, glaciers and polar caps.

Among numerous accomplishments for which NASA can claim credit is the first measurements of the steady but miniscule motions of the Earth's tectonic plates, which along with images of the continents and a global map the seafloor from space, provided verification and a substantive improvement in our understanding of the theory of plate tectonics. These observations along with spacecraft gravity and magnetic measurements that reveal the nature of the Earth's interior have collectively revolutionized our understanding of how Earth's surface has been shaped by the dynamic forces associated with heat loss from the planet's interior.

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. Opportunities should be selected 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. Smaller missions with focused objectives should be combined with flagship missions with ambitious objectives or challenging destinations.

The Moon is 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. Many more scientifically important areas undoubtedly exist, such as within polar craters that don't experience sunlight and may contain water ice, or within a huge farside basin that exposes material from deep within the Moon's crust. With numerous missions en route 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 materials 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 of 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 illuminate the challenges that would be faced regarding hazard avoidance, in the event that such a body is one day discovered to be on a trajectory to impact Earth.

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 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, in which I participated, that forms the plan for moving ahead. 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. Missions to study solar and Earth radiation, soil moisture, changes in the heights of ice caps, and land and ice surface deformation are justifiably recommended with high, near-term priority.

One of the most remarkable discoveries in space science over the past couple of decades has been the detection of planets around other stars, also known as extrasolar planets. After years of unsuccessful searching over three hundred of these objects are now known and their rate of discovery is rapid. Detection of these objects is mostly indirect, by tiny measuring 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 great challenge in coming decades 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 coordinated sensor arrays are key in realizing this 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 enable, 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 surprising outcome of the Apollo Program is the number of 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 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 unfortunately 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. 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.

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 working on an exciting 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 inspiring future careers in science, math and technology.

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.