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Dissertation on

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Importance Of Interplanetary Flight To Our Knowledge Of The Universe And Of The Development Of The Earth.

Good morning ladies and gentlemen. It is a great honor to be here and a great complement to be awarded this ....

Professor Buongiorno suggested I speak to you this morning about the importance of planetary exploration to our knowledge of the universe and of the development of the earth, and of my contributions to interplanetary projects, especially Voyager, Galileo, and Cassini. My experience with spacecraft engineering and development extends over forty-three years, yet I am in awe of standing before so distinguished an audience as this, distinguished scholars, professors, students whose roots, going back to Roman times, represent well head of western engineering. The world stands in awe of what those early engineers achieved and the durability of those achievements, for after all durability is the essence of good engineering and you live every day with constant reminders in remarkable abundance.

Therefore it is with great humility that I accept Professor Buongiorno's suggestion to discourse on the importance of planetary exploration, since this is really a question for the science community to debate, and I am a far cry from a scientist.

I spent the first half of my career as an engineer. As engineer's job is to make things that work, and to have them continue to work for long times in hostile and sometimes unpredictable environments. I was good at making things work.

The second half of my career was devoted to engineering management. A manager's job, at least in my view, is to make things happen or to create an environment in which engineers and others can make things happen. Good managers, again in my view, manage affairs, not people. I was also pretty good at making things happen. I didn't believe in managing people, the people I was lucky enough to work with didn't need to be managed.

So what can an engineer turned manager say about the importance of planetary exploration to our knowledge of the Universe? To borrow a phrase made popular by Carl Sagan, we know that the Universe consists of literally billions of galaxies, and that each galaxy consists of billions of stars, each one a solar system in its own right.

We also know that there are more solar systems in the universe than there are grains of sand on the Earth. Our solar system is just one of those grains of sand. What can we learn about the whole of the Earth from studying just one of its grains of sands? The extent of our own solar system is so enormous on a human scale as to make it unimaginable to most people, yet the extent of our galaxy is so much greater, and the Universe greater still. The enormity of scale is one of things that make questions about the Universe so difficult for most people to grapple with.

For example, if we imagine the distance from the Sun to Saturn, a distance of ten astronomical units, scaled to just one centimeter, then our nearest neighbor in the Galaxy, Alpha Centauri, would lie at a distance of more than 250 kilometers; farther than from Roma to Napoli

So when we speak of the importance of interplanetary flight to our knowledge of the Universe, people might well ask, "What can you learn of the Earth by studying just one grain of sand?" What can be known of our Galaxy, much less the Universe by exploring just one square centimeter of soil in the Borghese Garden?

It may not be possible to answer these questions in the time span of just one or generations of human endeavor. A similar question could have been asked of the Phoenicians who plied the shores of the Mediterranean, never venturing far from the coastline. In a sense that period of history can be thought of as the first era of exploration. That was the era of learning how to build and operate sailing ships and the most rudimentary forms of navigation. Those early explorers had no real means of navigation, no valid maps and no reliable means of communication. A thousand years or so later the Vikings were not able to do much more, although they did manage to navigate their way to North America and back. This first era of exploration lasted a long time by the standards of today, and progress was slow.

The second era of exploration began with Columbus and those that followed him. Could the Phoenicians or the Vikings have imagined the second era of exploration? The era of going out far beyond the then know lands and discovering what was out there. And what about the third era, the era of small expeditions going frequently, of bringing back samples from many specific targeted regions of the world. Archeological forays of all sorts typified the third era, forays by the explorers the likes of Jacques Cousteau to understand in detail the richness and natural treasures of our own environment.

In a similar way we may reflect on the eras of planetary exploration. The first era, like the first era of Earth exploration was an era of just learning to get there. This era, lasting roughly through the 60's and early 70's was typified by many series of missions of both USSR and USA origin. Families of spacecraft like Sputniks, Zonds, Veneras, Rangers, Pioneers and Mariners come readily to mind.

The earliest missions were to the Moon followed by missions to Venus and Mars. There was an amazing array of launches in those years, a total of ninety-four, with many failures. In fact, of the nineteen launches to Venus from 1961 through 1973, eleven failed. Of the eight successes, three were USSR and five were USA. During that same period there were sixteen launches to Mars, only four of which were successful.

Both the USSR and the USA adopted the practice of developing families or lines of spacecraft design, and introducing incremental improvements from mission opportunity to opportunity. Several families of spacecraft were used for these early missions, including Rangers, Surveyors, Mariners, Pioneers, Lunas, Sputniks, Zonds, Veneras, and Mars.

Although many of these missions were exciting in their own rights, in aggregate there was not a lot of scientific discovery. The overall success rate of the first era was only about 43%. The first era was really about learning how to get there.

Moon – First Era

Pioneer	1 for 4	1958-1959	USA
Luna	12 for 24	1959-1976	USSR
Ranger	3 for 9	1961-1965	USA
Sputnik	0 for 5	1962-1963	USSR
Cosmos	0 for 3	1966-1969	USSR
Surveyor	5 for 7	1966-1968	USA
Lunar Orbiter	5 for 5	1966-1967	USA
Total	26 for 57	1958-1976	45%

Venus – First Era

Venera	5 for 8	1961-1972	USSR
Mariner	3 for 4	1962-1973	USA
Sputnik	0 for 3	1962-1962	USSR
Zond	0 for 1	1964	USSR
Cosmos	0 for 3	1970-1972	USSR

Total	8 for 19	1961-1972	42%

Mars – First Era

Sputnik	0 for 2	1962-1962	USSR
Mars	0 for 7	1962-1973	USSR
Mariner	4 for 6	1964-1971	USA
Zond	0 for 1	1964	USSR
Total	4 for 16	1962-1973	25%

Jupiter/Saturn - First Era

Pioneer	2 for 2	1972-1973	USA
Grand Total	40 for 94	1961-1976	43%

The second era of planetary exploration was the era of learning what was out there. The second era started with the successful Venera 9 and 10 missions and two successful Viking missions in 1975. It ended with the launch of Cassini in 1997.

In the middle of this era, the USA discontinued the practice of launching two launches in each opportunity, as was the habit of both the USA and the USSR. Emboldened by a string of successes, and under the pressure of limited resources due to the higher costs of the more ambitious mission concepts of the second era, the USA began the practice of launching a single spacecraft for each mission opportunity. It could be argued that this practice served the USA program ill since Mars Observer, a single spacecraft launched to Mars, failed. However the likely failure mode was systemic and even had there been a twin sister spacecraft, it would likely have suffered the same fate. Furthermore the USSR, having launched two Phobos spacecraft to Mars lost them both, reinforcing in the minds of some the propriety of the single launch approach.

In any case the USA program evolved to be a single one of a kind spacecraft approach, specifically tailored for each new mission. Meanwhile the USSR continued its practice of developing families of spacecraft and launching multiple spacecraft for each mission opportunity. Although there were only twenty-nine launches in the second era, the success rate was much higher, about 75%. In general the scientific discoveries were rich and rewarding giving both scientists and lay people alike a new view and new understanding of our solar system and the neighboring planets within it. The richness of the results from the second era has prompted many to label this era, the Golden Era of Planetary Exploration.

Venus – Second Era

Venera	8 for 8	1975-1982	USSR
Pioneer Venus	2 for 2	1978	USSA
Vega	2 for 2	1984	USSR
Magellan	1 for 1	1989	USA
Total	13 for 13	1975-1989	100%

Mars – Second Era

Viking	2 for 2	1975	USA
Phobos	0 for 2	1988	USSR
Mars Observer	0 for 1	1992	USA
Total	2 for 5	1975-1992	40%

Jupiter/Saturn – Second Era

Voyager	2 for 2	1977	USA
Galileo	1 for 1	1989	USA
Cassini	1? for 1	1997	USA
Total	4? for 4	1977-1997	100%?
Grand Total	19? for 22	1975-1997	86%?

The third era, which began with Mars Pathfinder, the first of the Faster-Better-Cheaper missions, will be the era of going often and bringing back samples. Mars Pathfinder has generally been recognized as the current standard for Faster-Better-Cheaper. Mars Pathfinder cost less than $300 million dollars, 30% less than Mars Global Surveyor, less than a third of Mars Observer. However the following two missions, Mars Climate Orbiter and the Mars Polar Lander Mars Pathfinder both failed. Each of these missions was more complex than Pathfinder, and carried three times the science complement, yet were built for a total cost of less than the Pathfinder mission alone. The implementation for these missions simply pressed the boundaries of Cheaper too far. Both succumbed to simple human errors, which should have been discovered and corrected in the normal course of development.

People are human, and mistakes will happen. Space is an unforgiving environment, and our development systems need to be tolerant of errors, and robust enough not to succumb to the simple mistakes of single individuals. There were excellent, experienced people working on the Mars Climate Orbiter and Mars Polar Lander. The trouble was, there just weren't enough of them. Valuable lessons were learned from these failures about the necessary and appropriate nature of checks and balances and safety nets that must be integral to every planetary mission, Faster-Better-Cheaper or otherwise.

Since the third era is just under way, only a partial listing is available.

Mars – Third Era

Mars Global Surveyor	1 for 1	1996	USA
Mars Pathfinder	1 for 1	1996	USA
Mars Climate Orbiter	0 for 1	1998	USA
Mars Polar Lander	0 for 1	1999	USA
Total	2 for 4	1996-?	50%

The third era would seem to be off to a rocky start indeed. We shall have to wait to see what the future will bring. The USA is planning to launch an only an orbiter in 2001 in place of the orbiter and lander that had been planned prior to the loss of Mars Climate Orbiter and Mars Polar Lander. Likewise the entire Mars Program, which had been focused on returning a sample from Mars in 2007 with launches from Earth in 2003 and 2005 is under review, and will almost certainly evolve into something quite different. The large lander with sample return capability will not be launched as planned in 2003. It now seems likely that either a much simpler lander without sample return capability, or perhaps just an orbiter to recapture the science lost from Mars Climate Orbiter will be launched in 2003 instead.

It is clear that Mars will be the focus of the third era, but missions to comets, asteroids, Europa, and Pluto are also in the planning or execution phase. In fact one mission, called Stardust, is currently in the process of collecting dust from within the tail of a comet. After the dust is gathered and interred within an aerodynamic capsule, the Stardust spacecraft will be navigated on to an earth return trajectory and, after entry into the Earth atmosphere over the Utah desert, the capsule will be retrieved. Examination of this dust likely will reveal the nature of the early solar system -- before the formation of the planets and their moons. The Stardust spacecraft is also collecting interstellar dust samples at certain points in the mission, and thus will provide clues to the nature of the interstellar environment as well.

It is with a great sense of personal pride and gratitude that I look back on my involvements with the Ranger and Mariner missions of the first era, and the Voyager, Galileo and Cassini missions of the second era. I began my career at JPL in 1956 before the start of the space age and the founding of NASA. As a young engineer I worked on both the early Explorer and Pioneer spacecraft. I was privileged to be the chief architect of both the Ranger and Mariner series of spacecraft, and led the design teams for both Ranger 1/2 and Mariner 3/4 designs. Mariner 1 and 2 were actually descendants of the Ranger series. Ranger spacecraft were designed for operation in the Earth-Lunar region, and were ill suited to interplanetary operation. The Mariner 3/4 design was the first USA spacecraft designed truly for interplanetary use.

Later I held engineering management positions in several of the Mariner programs, including Mariner 6/7, the 1969 missions to Mars and Mariner 10, the 1973 mission to Venus and Mercury. Still later it was my privilege to manage three of the most technically challenging and complex planetary missions undertaken by NASA; Voyager, Galileo, and Cassini.

Voyager 1 and 2, still operating and returning useful scientific data nearly twenty-three years after launch are truly voyagers of discovery. The wealth and diversity of knowledge about the four major outer planets of our solar is unlikely to be matched by any future mission within our lifetimes and perhaps not within the lifetimes of our children.

The Galileo spacecraft has provided an abundance of in depth understanding of Jupiter and its four Galilean satellites from which the mission takes its name. Galileo, the spacecraft, improved the findings of Voyager by operating for more than twice its planned prime mission objective of two years in orbit at Jupiter. Galileo made multiple close up observations of each of the Galilean moons, compared to the single and relatively distant Voyager flybys. During those years, Galileo made repeated close observations of the Galilean satellites, fifty to one hundred times closer than Voyager, and with instruments many factors of two better than the Voyager instruments, both in spatial and spectral resolution.

During the mission, Galileo's mesh antenna failed to deploy properly, making it useless for communications, and seriously compromising the science expectations. With the success of the mission seriously threatened, a mission recovery plan evolved and a high profile major development activity was put in motion. The recovery plan required an extensive reprogramming of the Galileo on board computers to incorporate modern data compression and coding algorithms, a reconfiguration of the on-board computer and communication equipment, the development and implementation of new highly efficient ground based decoding system. In the end, and contrary to the dire predictions of wags and doomsayers, the mission has returned more and higher quality data than even its staunchest supporters cold have foreseen.

It is interesting to note that this happy state of affairs begat another. The problem with the Galileo antenna convinced the Cassini development team to select a rigid carbon composite antenna. No existing source for this type of antenna existed in the United States, and the search for a suitable high quality supplier led us to Alenia Spazio, and ultimately to the very successful partnership between ASI and NASA for the Cassini mission.

The Galileo team successfully dealt with a variety of technical challenges during development. One of the most formidable had to do with the precision pointing and stability requirements for the remote sensing instruments. An inertially stabilized pointing platform for the imaging system and the other remote sensing instruments had to be mounted to the spin stabilized Galileo spacecraft. The spinning spacecraft was an ideal platform for the in situ instruments, which required four pi steradian viewing continuously throughout the mission. The spinning spacecraft was an excellent carrier of the high gain antenna, since the spin axis could easily be pointed to the earth, and for the radioisotope thermo-electric generators, but as a base for the high precision pointing platform.

Another had to do with the requirement to operate for two years in the intense Jupiter radiation environment. The Voyager mission provided good information on the electron radiation environment, and the Galileo designers new how to cope with it. However Galileo employed a new generation of lower power faster integrated circuit types. Although these newer devices were hard to the electron radiation they turned out to be extremely sensitive to high-energy heavy ions, and subject to a phenomenon, which came to be known as Single Event Upsets or SEUs. The older slower more power using integrated circuits was not susceptible to this effect. It was until well into the development of Galileo that this phenomenon was recognized. A whole new family of integrated circuits was developed by Sandia National Laboratory specifically for Galileo. The new family of integrated circuits wee designed to be pin for pin replacements with the existing family which not only salvaged the mission, but also permitted Galileo to salvage the enormous investment in flight computers and the all of the in flight software development.

The development of the Galileo presented not only daunting technical challenges but also political challenges. The political challenges had to do with maintaining project and technical momentum in the face of several major reprogramming episodes occasioned by a series of ongoing technical and schedule difficulties with the Shuttle development program. Since the Galileo and Shuttle development programs were running in parallel, and since Galileo was mandated from the start to be a Shuttle payload, any slip in the Shuttle development or reduction on the Shuttle lift capability would require a corresponding change in the Galileo program. In fact this occurred not once, but four times during the Galileo development period. Maintaining program momentum and continuity of the program, while at the same time maintaining the continued support of the funding authorities was as great a challenge as the technical challenge. Even with escalating costs arising from the constant reprogramming, the expected scientific results provided compelling arguments that the project was still worth doing.

The Cassini mission with the Huygens probe promises to be as rewording in terms of scientific returns from Saturn as Galileo was from Jupiter, and is arguably the most complex and capable interplanetary spacecraft and mission design effort ever undertaken. It is also the largest in terms of mass and scientific instrument complement.

Cassini represents the combined contributions of the US space agency, NASA, the Italian space agency, ASI, and the US Department of Energy. Italy provided not only the high gain antenna, but also a very complex, state of the art four frequency feed system, a precision frequency translator, the heart of a gravity wave detection experiment, and the transmitter elements of the synthetic aperture radar. Titan's atmosphere is opaque, frustrating Voyager's attempt to image the surface. The radar will be able to provide global coverage of the moon's surface, while the imager on the Huygen's probe after it descends below the cloud layer will provide higher resolution coverage of the landing area.

The US Department of Energy provided the radioactive power sources for Cassini, and indeed for all of the outer planet missions flown to date and for the Viking missions to Mars. It should be noted in passing that future outer planet missions will also require these types of power sources. Future missions to Mars, if they are to have capability beyond the rudimentary capability of Mars Pathfinder, especially long duration presence on the surface, will require them as well. The technical challenges associated with flying these highly reliable long lasting power sources pale in comparison with the problems of properly acknowledging and addressing the concerns of a segment of the world's society. International partnership has proved effective way of sharing risks and rewards of space exploration. If these rewards are to be extended through continuing exploration there will likely need to be international participation in addressing the risks, both real and perceived, with the use of radioisotope power sources for long-lived planetary spacecraft.

The Huygens probe is provided by the European Space Agency, ESA. The Cassini spacecraft will carry the probe into orbit at Saturn. After four and half months in orbit, Cassini will release Huygens on target for entry into the atmosphere of Titan. Upon separation, contact between the spacecraft and the probe will be maintained by radio link. Huygens will transmit its scientific and imaging data to Cassini where it will be stored on board Cassini for subsequent retransmission to Earth. ASI, in addition to its direct participation in the Cassini spacecraft, also provided the radio transmitters and receivers for the relay link communications. Thus the high gain antenna, the synthetic aperture radar transmitter, the high frequency converter, and the Huygens relay link transmitter and receiver are all part of the Italian contribution to the Cassini mission. I must also note that the star camera on Cassini is an Italian product. Officina Galileo was awarded the contract to build the star camera after submitting the winning bid in competition with two US industry firms.

In all the combined ASI - ESA contributions represent about 40% of the total Cassini mission development cost including the launch vehicle. The Cassini mission is truly an international effort, surpassing on a pro rata basis, the International Space Station, even without the Shuttle launch costs for the Station.

As we reflect on the accomplishments of the first and second eras of planetary exploration we must not forget that the foundations for these accomplishments were laid by those who have gone long before us. Galileo and Cassini, for whom these spacecraft have been named, come immediately to mind, but there are many others as well. Isaac Newton, Leonardo daVinci, and Guglielmo Marconi, who received the Nobel Prize for Physics in 1909 for inventing radio communications, also come to mind. I guess one could say that these are but two examples of Italy's technological largess, first Cassini to France, and then Guglielmo Marconi to England. One could even go back to the medieval scholar Giordano Bruno who in 1584 wrote, "There are countless suns and earths all rotating around their suns in exactly the same way as the seven planets of our system. ....."

But closer in time we can also point to the late Guiseppe Columbo, a person I had privilege to know and work with when he was a visiting scholar at JPL, who was an early thinker on the practice of gravity assist trajectories, without which Voyager, Galileo, and Cassini would not be possible. Pepe was the first to recognize that multiple flybys of Mercury would be possible with the Mariner 10 Venus/Mercury. Through his insight and analysis we were able to transform the Mariner 10 mission from a single Mercury flyby two a triple flyby, greatly increasing the scientific yield from that pioneering first era mission.

What has Voyager, Galileo, and Cassini taught us of this grain of sand we call the solar system? The Voyager missions opened our eyes to the wonder and diversity of the outer regions of this grain of sand. All of the outer planets save Pluto have been scouted in as much detail as one week of flyby observations will permit, with astounding discoveries of active volcanism at Io, the ice covered surface of Europa, rings at Jupiter and Neptune, dense atmosphere of Titan, and the amazingly complex gravitational and electrical dynamics of the ring particles at Saturn.

It is too soon, at least for me, to foretell what the impact of our accomplishments in planetary exploration will be to our ultimate knowledge and understanding of the Universe. Nor do I suppose that those who have gone before us could have foreseen what the first and second errors have accomplished, although I must admit that the writings of Giordano Bruno could give one cause to ponder. At best we can hope that future discoverers, future generations will look back on the interplanetary accomplishments of our age as the foundations on which their own discoveries were based.

Having participated in the laying of those foundations has been a rare honor for me; exceeded only by the honor you do me today.

Thank you very much for the honor of being here.