WHY IS SPACE EXPLORATION SO EXPENSIVE?

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Three hundred eighty-six years ago, Galileo discovered the four large moons of Jupiter using only his newly-built telescope. When the NASA-JPL spacecraft named after him arrives at the same planet this week, it will have taken eighteen years and a billion dollars to get there., and it will still take a few hundred million dollars more to complete the mission and receive all the data. What accounts for the hundreds of millions of percent increase in costs between early seventeenth and late twentieth century science? There are several reasons for the increased cost of modern science: (1) we're trying to learn many more details about the planet, its moons, and its magnetic field than Galileo could ever hope to study; (2) this more detailed study requires complex equipment designed and built by hundreds or thousands of highly-trained experts; (3) the spacecraft must survive severe extremes of temperature, radiation, acceleration, and vibration; (4) special processes and testing are necessary to ensure the success of the mission in these hostile environments; and, (S) as all twentieth century car or home appliance owners and observers of the United States Congress know, things can go wrong with complex technological and political systems, and the Galileo mission has had both political and technical setbacks, Space exploration costs are therefore about people: those who build the equipment, and those who use it to increase knowledge.

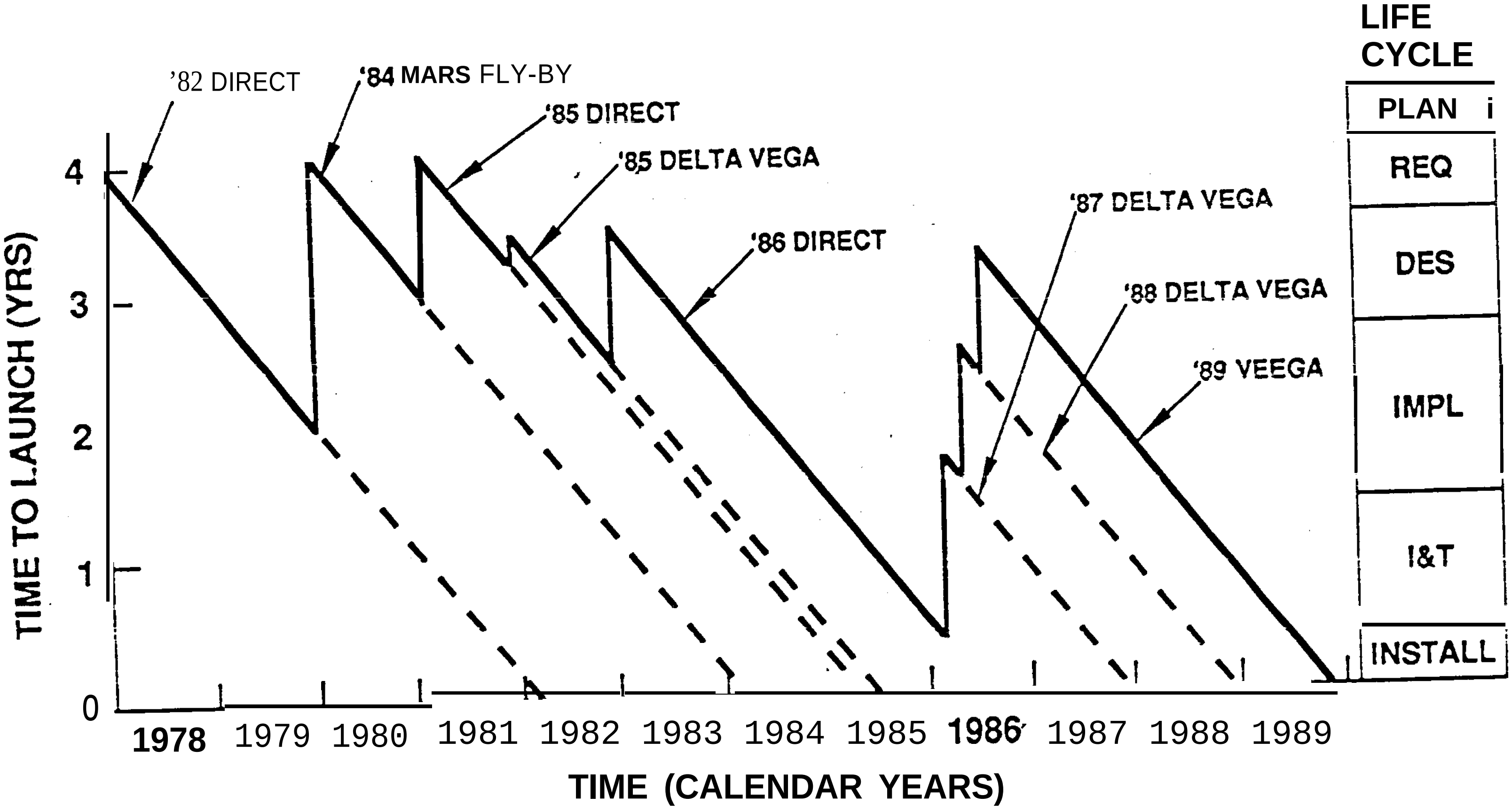
in the fall of 1609 Galileo improved his original three-power telescope to a magnification of thirty-two and was able to make history's first astronomical observations using the instrument which Dutch lens-grinders had recently invented. Training it on several objects in the night sky, he discovered Jupiter's moons (which he prudently named after a Medician student and patron), the phases of Venus, individual stars in the our Milky Way galaxy, sunspots, and the craters on Earth's moon. At a modest expense he was able to cause an enormous increase in humanity's knowledge of our world. But his pioneering scientific advance was not made without commensurate research and development on instrumentation. He had learned of the principle of the telescope earlier that year in Venice, and, upon returning to Padua, he built his first low-power telescope. Seeking to improve it, he developed a proms for measuring lens curvature which revolutionized telescope construction and made it possible to build higher-power instruments useful for astronomical--and, of primary interest to his Venetian patrons, military--observation. His low-cost technology, combined with educated curiosity, produced large scientific advances, but he left to four centuries of astronomers the problem of filling in the details on his initial discoveries.

The NASA-JPL Galileo mission has much more ambitious goals than studying Galileo's *Sidera J4edicerr--the* four Galilean moons of Jupiter. in the centuries since January 7, 1610 when Galileo first observed the moons, Earth-based astonomers, two Pioneer spacecraft, two Voyager spacecraft, and the Ulysses spacecraft have increased the detail with which we know the Jovian system. Our present Galileo mission will take another major step by taking measurements within Jupiter's atmosphere, by getting even closer to the four major moons than Voyager, by mapping the details of Jupiter's magnetic field and the energetic particles it contains, and by making a long-term study of the planet itself. All this close observation over the two-year primary mission, during which the spacecraft will be in orbit around the planet, increases costs far above the expense of all previous studies of Jupiter. Whereas the Pioneer and Voyager spacecraft flew by Jupiter and went on to leave the solar system, Galileo must carry enough propellant to slow itself so that it can be captured by the planet's gravity. For the first time in history, an instrumented package will parachute into the atmosphere of one of the outer "gas giant" planets to measure directly, rather than by inference, the structure and composition of the hydrogen-helium atmosphere and its ammonia and methane clouds. While the probe studies the planet, the orbiter wilt make much more detailed studies of the moons and magnetic field. For example, whereas Voyager flew within 12,000 miles of Jupiter's moon 10, Galileo's closest approach will be 600 miles, enabling it to study lo's sulphurous volcanos in much greater detail than Voyager. All these measurements made near or within the planet's atmosphere (rather than from Earth or from a more distant fly-by spacecraft) carry the additional complication and expense of an environment that is very hostile to Earth-built electronics. Jupiter's radiation belts can cause transient and permanent damage to computers and to the spacecraft's control and communication electronics, while the probe must withstand the heat, deceleration stress, and crushing pressure of Jupiter's atmosphere. in one minute the orbiter must absorb more radiation than we on Earth absorb each year, and, while in Jupiter's radiation belts, the dose is hundreds of times higher. Thus, "easier," and much less expensive studies of Jupiter have laid the foundation for the Galileo mission to conduct much improved, but much more expensive, analyses from inside the planet itself and from a long-term orbit around the planet and near its moons.

Included in the equipment required to get this more detailed information from Jupiter is a communication system that must send the data across a half billion miles of space. Because of weight and power limitations, the spacecraft's radio only transmits an amount of power equivalent to that consumed by a refrigerator lightbulb. A large unfurlable antenna was therefore needed to focus the radio beam into a pattern directed toward Earth. Millions of dollars were required to build a small, lightweight, low power radio and unfurlable antenna. Other examples of the sophisticated and costly equipment necessary for exploring a distant planet are special computer chips resistant to the particles in Jupiter's radiation belts, and new technology in the instruments carried on both the orbiter and probe which study the planet's entire environment in much broader areas of the electromagnetic spectrum than just the visible light that Galileo could see through his telescope in the seventeenth century. Galileo's namesake orbiter carries several instruments, measuring wavelengths from very short ultraviolet waves, through visible wavelengths, and on to long infrared (heat) waves, and even longer radio waves. It also carries instruments to measure Jupter's magnetic field, to sense charged particles such as electrons, protons and Helium nuclei, and to sense dust particles throughout the spacecraft's journey. The probe that will enter the planet's atmosphere carries instruments that study the temperature, pressure, and deceleration of the probe as it descends. It carries a mass spectrometer which can detect chemical compounds and transmit the data through the orbiter to Earth, and instruments to study clouds, lightning, radio waves, and charged particles in Jupiter's radiation belts and atmosphere. In addition to the millions of dollars required to build this delicate equipment, over 100 scientists from six nations are funded to control the instruments and analyze the data.

These examples of costly equipment required to sense and return data from great distances could be expanded to include a radioactively-heated power system that must operate so far from the sun that solar cells are impractical, a guidance and pointing system which must point the instruments to an accuracy of a small fraction of a degree so that scientists can aim at especially interesting features, a navigation system that must deliver the probe to a 1000-mile diameter spot after travelling 2.4 billion miles, and a temperature control system that must protect the spacecraft from both the heat of travelling into Venus' orbit near the sun and to Jupiter's orbit hundreds of millions of miles away from the sun. But besides the immediate equipment costs, expensive processes and designs are used to increase the likelihood that the spacecraft can complete its mission. And many of these processes require engineers and scientists with post graduate degrees in disciplines that are also appropriate for the defense, aerospace, electronics, computer, and communication industries; so scientific organizations must compete with industry for these expensive, skilled people. For example, years before the spacecraft is launched, experts in celestial or orbital mechanics and astronomy must design the orbit and mission that the spacecraft will fly; and this continues throughout the design, construction and flight phases of the mission as political, funding, and technical changes occur. Because the spacecraft must survive hostile launch and space environments, many tests must be run to verify the soundness of the design. This also takes large capital expenditures for test facilities, plus specialists with years of experience in operating, for example, large vacuum chambers which can simulate both the vacuum and cold of outer space and the intense heat of the sun near the inner planets such as Venus or Mercury. And even seemingly mundane processes such as keeping track of design paper, an activity called "configuration management," can consume many specialists for several years and must be included in total mission costs. Finally, the designs themselves must be robust to withstand the shock, vibration, heat, cold, and vacuum that the spacecraft will experience. For example, the Galileo probe will make the fastest entry into any planetary atmosphere in history, causing high mechanical stress on its structure and extreme temperatures on its heat shield. The orbiter itself must withstand temperatures from over 300 degrees below zero (Fahrenheit) to 400 degrees above zero. Since a car on Earth can only operate from a few degrees below zero to about 100 degrees above, these extreme requirements require overdesigning the equipment in some cases so that it includes "safety factors," or capabilities that are greater than 100°/0 of the expected real requirements for the design. Some equipment is even duplicated so that if one part fails another takes its place, or a totally different method is provided for accomplishing a critical function. Individual parts themselves are expensive, especially for a flight to Jupiter, because they are designed to withstand the intense radiation of Jupiter's radiation belts, and must be produced by costly manufacturing processes in companies experienced in nuclear radiation environments.

The final causes for the large expenses of twentieth century science include failures and changes in program direction. These can range from the merely irritating to catastrophic, and even tragic. NASA and JPL lost the billion-dollar Mars Observer spacecraft in 1993 just as it was to be placed into orbit about Mars from a cause that will forever remain unknown. The Galileo mission was compromised shortly after launch when its high gain antenna failed to deploy fully, so work-arounds have been designed to retrieve much of the potentially lost data, so that Galileo will continue to be a significant scientific success. Years of delay and hundreds of millions of dollars of increased costs were added to Galileo by the tragic loss of the Challenger shuttle with its astronauts in 1986. As shown in the accompanying diagram, over its twelve-year development, Galileo was sent back to the design phase several times due to the Challenger tragedy and to congressional or NASA redirection, especially in its early years. Devised by Neil Yarnell, manager of JPL's spacecraft system engineering section, the diagram shows on the left-hand vertical axis how the Galileo mission was expected to launch in four years when it was begun in 1978. The right-hand vertical axis indicates the project life-cycle phase corresponding to the time to launch of the left-hand axis: planning ("PLAN'), requirements definition ("REQ"), design ("DES"), implementation ("IMPL"), integration and test ("I &T"), and installation on the launch vehicle ("INSTALL"). The labels for the sloping lines indicate the type of trajectory each mission was supposed to fly to Jupiter. For instance the last sloping line from the 1986 Challenger tragedy to the 1989 launch--the "89 VEEGA" which Galileo is actually flying--stands for" 1989 Venus-Earth-Earth gravity assist," indicating that Galileo got three energy boosts on the way to Jupiter: one from Venus in 1990, and two from Earth in 1990 and 1992. All these changes requiring that Galileo be sent back to the planning, requirements definition, or design phases are very expensive since hundreds of people must redo much of the work they had just completed. Although he was familiar with the scope and complexity of comparable governmental projects of his own time, Galileo Galilei probably wouldn 't recognize the technical challenge of the twentieth century effort to continue planetary exploration in his name. He would almost certainly understand the spirit, motivation, and enthusiasm with which planetary science is carried out.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