Solar System Exploration: A Vision for the Next 100 Years

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Space travel is multitiered, but the primary challenge is propulsion. Associated costs continue to stall significant advances for both manned and unmanned missions. While there continues to be a hope that commercialization will lead to lower launch costs, markets for deep space remain elusive. Hence, initial development beyond Earth orbit will likely remain government sponsored. Against this backdrop, we consider the linkage of scientific goals, current efforts, expectations, current technical capabilities, and requirements for the detailed exploration of the solar system and consolidation of off-Earth outposts. Over the next century, distances of 50 astronomical units could be reached by human crews, but only if resources are brought to bear by international consortia.

INTRODUCTION

"Where there is no vision the people perish."[1]

Proverbs, 29:18

A great deal of new interest in space and space travel has arisen with the publication of the Aldridge Commission Report,[2] efforts to develop current space tourism, and an ongoing series of missions to provide scientific exploration (notably of Mercury, Mars, Saturn, and Pluto). NASA science planning has typically undergone a "road mapping" activity once every 3 years. This type of planning has been extended in the work of the Aldridge Commission.

Nonetheless, these exercises typically project only into a "far future" of typically 20 years hence, if that much,[3] usually—and rightly—stating that policy goals and technologies will change so radically on longer timescales that further extrapolation must be relegated to the realm of science fiction or fantasy. However, as we have now entered the second century of aeronautics, we have a baseline to look back on. We can see what people thought might happen in the previous 100 years, what really did happen and why, and perhaps more to the point, at what cost.

Especially following the technical gains in rocketry and atomic power brought about by World War II, there was much speculation about what we could, and would, do in space. Historically, space exploration has always been aligned with an outward look. In the beginning, the vision was one of manned flights to Earth orbit and beyond. While that outlook gave way to robotic probes going to a destination first, it has always, at least to the majority of people, been with the idea that humans would eventually follow.

The Art of Prediction

Future predictions can be, and many times are, misleading. An example is the prediction from the early days of the automobile that it would soon be supplanted by personal airplanes for local travel, a scenario yet to be borne out. At the same time, such predictions—if grounded in limits imposed by physics and chemistry and for which there is a technology path—can work out. Usually, the implementation is not as easy as originally thought because the devil always is in the details. An example is Von Braun's 6400-metric-ton (MT) ferry vehicles for carrying 39.4 MT to a 102-km orbit for building Mars transfer vehicles.[4,5] The propellants for three stages were nitric acid and hydrazine.

The Space Shuttle, on the other hand, is a single vehicle with detachable solid rocket boosters (using solid propellant) and a throwaway main tank carrying liquid oxygen (LOX) and liquid hydrogen (LH2). It is a 2040-MT vehicle that can carry 24.4 MT to a 204-km orbit. The Shuttle has better performance than Von Braun's vehicles, but with less cargo because a realistic altitude is higher than he envisioned. Von Braun also envisioned the driving cost for his Mars mission at $500 million for about 5.3 million MT of propellant for the ferry ships to transport the propellant and supplies to Earth orbit; this translates to ≈$3.6 billion (in FY1996 dollars) during 950 flights by 46 vessels in 8 months (1 ferry flight every 10 days, 6 ferries assumed to be out of commission at any given time). Given the historical costs of building and operating four Space Shuttles, these are obviously not the resilient, cost-effective vehicles Von Braun had in mind. However, his calculations may yield insight into some of the top-level requirements of a human mission to Mars that may translate into performance required of the Crew Exploration Vehicle (CEV) if it is to be up to that task.

Key Mission Elements

Every mission has four key elements: the case for going, the means to go, an agreement to go by all stakeholders, and a source of funds sufficient to finance the expedition.

The case for the Apollo missions was the geopolitical situation, whereas the reasons for going for robotic missions were a combination of supporting Apollo goals (early on), science mixed with geopolitics (the United States and Soviet Union were both sending missions to the Moon, Venus, and Mars early on), and science, with some level of lingering international competition (Mars Express and Mars Global Surveyor) and international cooperation (Cassini/Huygens).

The means for going, space technology, has a long history[6] but grew in large part from the V-2 work of World War II and later ICBM development programs during the Cold War. The end of that geopolitical competition, combined with the current lack of deep-space commercial activity and limited Earth-orbital satellite markets, has led to slower development in many areas, especially where the radiation hardness of electronics is an issue.

Stakeholders include advocates of a mission, non-advocate reviewers (whose job is to see that invested monies are well spent), those who are forwarding funds, and those who can be impacted positively by success and negatively by failure. A well-thought-out strategy includes all stakeholders and provides both the framework and substance of an agreement to do the mission.

Finally, there must be a source of funds sufficient and available in the needed time-phasing to support the endeavor. Such programmatic support has typically come from the government exclusively for non-communications satellites. New missions usually have significant new technologies that require implementation (and sometimes unanticipated development) and involve the next step in a non-routine, non-recurring scenario of exploration. Costing of such endeavors is tricky at best and requires some "adequate" level of reserves that can be drawn upon to support the resolution of unanticipated development problems. At the same time, some members of the stakeholder community will be pressing to keep outlays as low as possible. While such tensions are "obvious," space missions, as with other large engineering endeavors, involve large sums of money that are not easily turned off mid-project if the budget is exceeded. Overruns and missed schedules are, and have been, tolerated on many individual programs because the termination cost can be too high if sufficient funds have already been spent. However, such overages can put a programmatic end to follow-on missions.

System of Systems

Currently, and for much of the foreseeable future, deep-space missions (defined as non-Earth orbit), and certainly those beyond the Earth–Moon system, will be driven by, and/or framed in terms of, science return from various solar system bodies. While beginning with the Moon and Mars, the espoused vision in the main reaches throughout the solar system. The science objectives are thus the generic drivers that trace down through the hardware requirements. Appropriate analyses should then be able to provide results that answer the posed questions. The demonstration of such closure (at least in principle) is part of the strategy that must be developed up front (Fig. 1). The global requirements that drive the mission design, implementing technologies, and especially cost include answers to these questions:

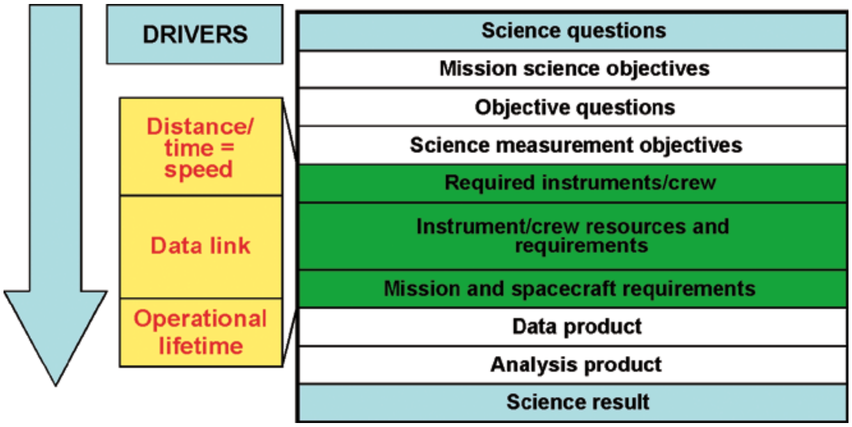

Figure 1. Answering solar system science questions is a "system-of-systems" problem.

1. How far are we going? How long can we take? Is this a flyby, rendezvous, or return mission? That is, what total velocity change capability is required?
2. What are the data link requirements, bandwidth, and coverage continuity?
3. What is the required operational lifetime—driven by both point 1 and reserve requirements—based on autonomy, sparing philosophy, and consumables, both for the mission and for a human crew, if there is one?

THE PAST

"When change is absolute there remains no being to improve and no direction is set for possible improvement: and when experience is not retained, as among savages, infancy is perpetual. Those who cannot remember the past are condemned to repeat it."[7]

G. Santayana

Beginnings

The conquest of the solar system has been a favorite theme of science fiction writers for well over 100 years. Modern interest in Mars was kindled by Percival Lowell's suggestion of intelligent beings on that planet, a theme taken up in the early writings of Edgar Rice Burroughs[8] and others. Contemporaneous technical work by space pioneers Tsiolkovskii, Oberth, and Goddard laid the foundations for the technical realization of travel enabled off Earth. Realization of space travel has been more difficult. As with many large-scale technical innovations, national interests provided the main means of development, in this case World War II and the ensuing Cold War. The first activity supported the development of the V-2, and the second enhanced and consolidated those technical efforts, first in the development of ICBMs and later in the development of the launch vehicles currently used for manned, commercial, and scientific exploration.

Immediately following World War II, Clarke[9] and others[10–12] discussed the application of fission power to rockets to enable new capabilities. Clarke notes:

> Before the year 2000 most of the major bodies in the Solar system will probably have been reached, but it will take centuries to examine them all in any detail. Those who seem to think that the Moon is the goal of interplanetary travel should remember that the Solar system contains eight other planets, at least thirty moons and some thousands of asteroids. The total area of the major bodies is about 250 times that of the Earth, though the four giant planets probably do not possess stable surfaces on which landings could be made. Nonetheless, that still leaves an area ten times as great as all the continents of the Earth—without counting the asteroids, which comprise a sort of irregular infinite series I do not propose to try to sum.

Clarke[9] also adds that the practical uses for (manned) space stations in Earth orbit would be as meteorological observation stations and as relays for worldwide television broadcasting.

The Launch Record

Beginning with Sputnik I in October 1957 and going through calendar year (CY) 1998, there were 3973 successful space launches, the majority conducted by the United States (1161) and the former Soviet Union and Russia (2573). However, most of these missions have been to Earth orbit. Even extending the database of lunar and planetary missions through CY2004, there have only been 139, of which 112 were successful. Thus, less than 3% of all space missions launched through 2004 had gone beyond Earth orbit (Fig. 2).[13,14]

Interplanetary Robotic Probes

Discussion of Earth-orbiting satellites accelerated during the planning for the International Geophysical Year (IGY)[4] and culminated with the Sputnik launch of October 1957. The problematic U.S. Vanguard project was moved aside, and the successful U.S. Explorer I satellite was placed into orbit in January 1958. NASA was established in 1958 to coordinate all non-military, scientific space activities. A combination of scientific and national goals led to an acceleration of satellite launches, with an early interest in lunar and later Venus and Mars probes. Trends are shown in Fig. 2. Historically (in the United States at least), a focus on the Moon (Ranger, Surveyor, Lunar Orbiter) and early interplanetary probes (Pioneer 5–9 missions to measure interplanetary radiation) supported the manned lunar landing effort announced by President Kennedy in May 1961. Both the

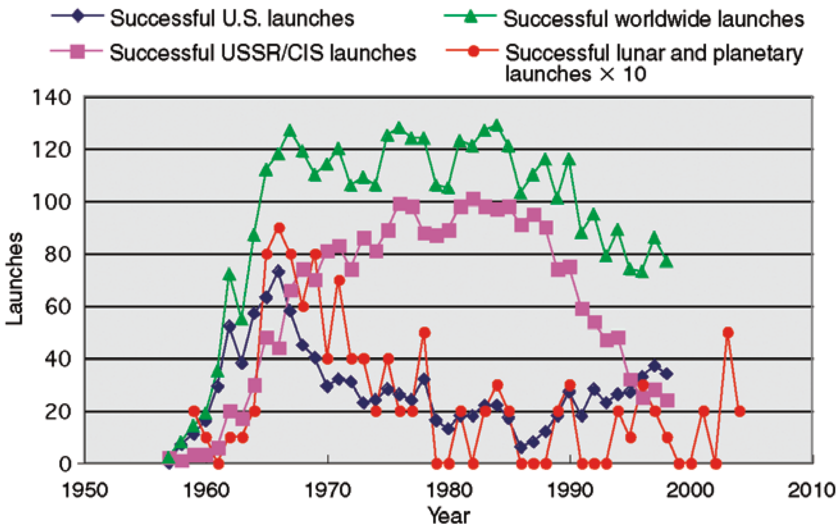

Figure 2. Historical launches from 1957 to 1998. Successful interplanetary launches through 2004 have been added from NASA websites. All launches, including the percentage that were beyond Earth orbit, continued to grow until about 1965 when the number of U.S. launches began to taper off. The downturn in USSR/CIS (Commonwealth of Independent States) launches coincided with the end of the Cold War era. Lunar and interplanetary launches include those of all countries. Following a peak in the mid-1960s, launches have tapered off to 10% or less of the United States–only launches.

United States and the Soviet Union sent scientific probes to Venus and Mars.

The Outer Planets

Following the Apollo Program success, NASA focus turned toward the outer solar system. Pioneers 10 and 11 were the first probes to reach Jupiter and Saturn, respectively, and showed that spacecraft could traverse the asteroid belt with a minimum number of dust hits. Voyager 1 and 2 spacecraft that were descoped from the original Grand Tour mission concept[15] followed up with more intensive detailed studies of the Jupiter and Saturn systems. Voyager 2 followed the original Grand Tour trajectory, providing the first in-depth studies of the Uranus and Neptune systems. Although the Pioneers have fallen silent, the two Voyagers continue to broadcast back to Earth data on the interplanetary medium and its interaction with the very local interstellar medium.

Voyager results motivated a desire for more in-depth study of the outer solar system. A detailed study of the Jovian system was provided by the recently completed Galileo mission. Such studies of the Saturnian system are continuing with the Cassini/Huygens mission, a joint effort by NASA and the European Space Agency (ESA), that reached the Saturn system in July 2004.

Venus

Venus exploration can be split into orbital missions that probed the space environment of the planet using radar to penetrate the permanent cloud deck and landers that gave brief spot measurements of conditions at the surface. From the mid-1960s to the mid-1980s, the Soviet Union built up a capability culminating in photographs and composition data from the surface of Venus.

Flybys of Venus by the U.S. probes Mariner 2, 5, and 10 measured the global temperature of the planet, showed the lack of a global magnetic field, and provided information on the interaction of Venus with the solar wind and the global cloud circulation pattern. (Mariner 2 also provided conclusive evidence for the solar wind, and Mariner 10 went on to provide the first—and only to date—observations of the planet Mercury.)

Orbital studies by Pioneer 12 (also Pioneer Venus Orbiter [PVO]), atmosphere studies by Pioneer 13 (and Pioneer Venus Multiprobes), and radar studies by PVO and later the Magellan spacecraft in the 1990s have completed Venus investigations to date. Venus Express, an ESA mission based on the successful Mars Express spacecraft, is now operational in orbit about Venus.

Mars

While Mars first evoked public interest in solar system travel, initial results proved to be discouraging. Mariner 4's flyby provided 21 pictures showing a cratered terrain and very low atmospheric pressure measurements. More data were accumulated by the U.S. Mariner 6, 7, and 9 spacecraft and by the Soviet Mars 2–7 probes.

The United States made an all-out effort to determine whether life existed on Mars with the Viking 1 and 2 missions that consisted of orbiters, which mapped the planet and its satellites Phobos and Deimos, and landers. The landers carried sophisticated atmospheric and chemical instruments for measuring atmospheric properties and detecting life and were powered by radioisotope thermoelectric generators. While the changing of the Martian seasons was studied by the landers, the life-finding experiments provided disappointing and contradictory results, now thought due to the highly ionizing conditions in the top layer of Martian regolith at the landing sites.

A hiatus in robotic Mars exploration ensued for 20 years, including the failed Soviet Phobos missions of 1988 and the failed NASA Mars Observer mission of 1992. However, Mars exploration is back as a mainstay of world scientific investigation. Starting with the NASA Mars Global Surveyor orbiter (operational through late 2006 in extended mission), successful missions include NASA's Mars Pathfinder rover mission (the second of the agency's Discovery line of missions) and Mars Odyssey orbiter (operating), ESA's Mars Express Orbiter (operating), and NASA's Spirit and Opportunity rovers (operating in extended missions). Problems have continued as evidenced by the failures of Nozomi (Japanese Space Agency); Mars Climate Observer, Mars Polar Lander, and Deep Space 2 (all NASA); and Beagle 2 (ESA/UK lander).

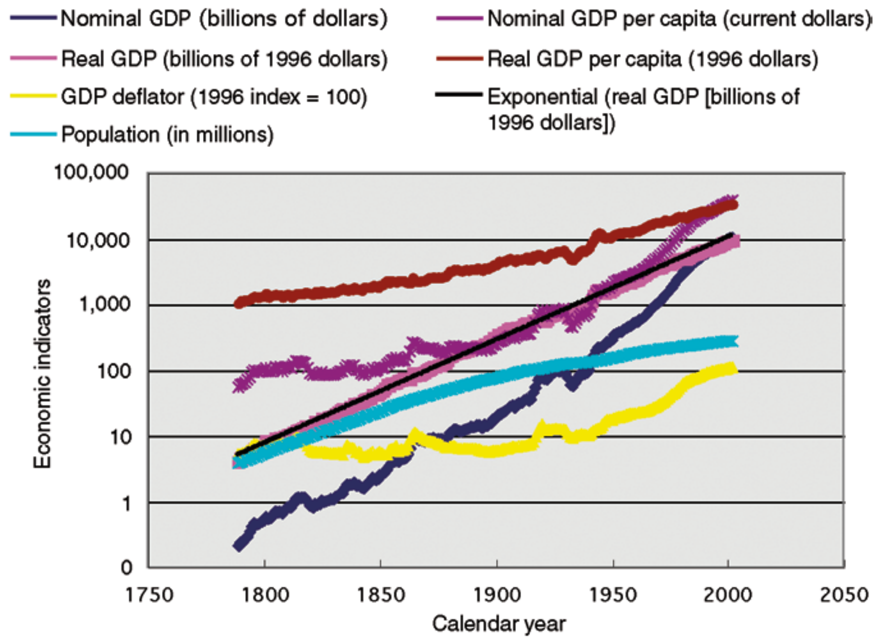

Figure 3. U.S. economic and population trends, 1789–2002.[16] The GDP in fixed-year dollars shows an e-folding time of ≈28 years.

Others

Other probes have visited Mercury and other small bodies in the solar system, and there are plans for future visits as well. As noted, Mariner 10 has provided the only close-up look at Mercury to date. The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission is now en route to the innermost planet, and ESA is proceeding with development of the multiple-spacecraft BepiColombo mission to Mercury. Multiple spacecraft have made close flybys of a variety of comets, including the Deep Impact mission that released an impact probe that hit Tempel 1. Various spacecraft have also flown closely by asteroids, including the Near Earth Asteroid Rendezvous (NEAR) mission to 433 Eros, which concluded with the first successful landing on an asteroid, and the Japanese Hayabusa mission to asteroid 25143 Itokawa, which is to return with a sample in 2010. New missions include the Dawn mission to the large asteroids Ceres and Vesta.

Capacity for Future Growth

Whether financed by governments or by private interests, space exploration is expensive. Unless and until commercial advantages can be identified for deep-space exploration, missions beyond Earth, and almost certainly beyond the Earth–Moon system, will remain financed by individual governments or international government consortia.

The capacity for such growth is therefore tied to economic activity and levels capable of supporting such continued expansion. Figure 3 shows records of U.S. economic indicators from 1789 through 2002.[16] During that time, this reconstruction of financial activity shows a gross domestic product (GDP) in fixed-year (1996) dollars increasing from ≈$4 to ≈$9400 billion as the population grew from ≈3.8 to ≈280 million, yielding a GDP per capita increase of a factor of ≈30 over ≈200 years. The economy exhibits an e-folding time of ≈30 years that has yet to show signs of decelerating. Although corresponding figures for developed and developing countries were not as readily available for this study, the continued economic capacity for human exploration appears to be present.

Manned Planetary Mission Studies

No human excursions have gone beyond Earth orbit except to the Moon with the Apollo missions. These expeditions included the lunar flybys of Apollo 8, 10, and 13 and the landings of Apollo 11, 12, and 14–17 (Apollo 7 and 9 were checkout missions in Earth orbit).

Das Marsprojekt

The first detailed study of manned planetary mission requirements was carried out by Von Braun[5] for a manned Mars expedition (in the appendix to a novel that was never published[4]). The plan provided for ten 4000-ton ships, 7 with a crew of 10 each, and 3 cargo ships. The 950 flights of three-stage ferry rockets would be required to assemble the flotilla in low-Earth orbit (LEO), each ferry using 5583 tons of nitric acid and alcohol (later modified to hydrazine) to put 40 tons into orbit (the Space Shuttle capability to LEO is ≈20 tons). While acknowledging the possibility of advances leading to nuclear rockets, Von Braun's scheme was based on nearer-term chemical technology, in which case there was a need of 5.3 million tons of propellant to assemble (and fuel) the Mars ships. About 10% of an equivalent quantity of high-octane aviation gasoline was burned during the 6-month operation of the Berlin Airlift in 1948–1949. The estimated total cost for launching the mission into Earth orbit was $500 million (now over $3 billion as noted earlier).

In discussing the many Mars mission plans, Portree[4] notes that Von Braun's thinking was influenced by the then-recent Antarctic Operation Highjump, a U.S. naval expedition in 1946–1947 consisting of 4000 men, 13 ships, and 23 aircraft. In the late 1940s Von Braun explicitly stated that such a mission would tend to resemble Magellan's expedition around the world; the Mars mission would need to be self-reliant and would cost as much as a "small war."

These factors resulted in a variety of NASA studies (Early Manned Planetary-Interplanetary Roundtrip Expeditions or EMPIRE[17,18]) and, after President Kennedy's 1961 speech, a focus on spacecraft architectural elements for reaching the Moon by the end of the 1960s. The goal was Mars, but many of the EMPIRE concepts included a manned Venus flyby on the return leg to minimize propellant requirements. Manned flyby-only missions were also advocated to drop probes, based on the (then) notion that robotic probes were too unreliable to drop probes successfully to the Martian surface (a notion borne out by the track record of robotic probes up to that time).

Magellan's Voyage

Recall that while this first circumnavigation of the world is considered to be one of the defining moments of exploration, it was entirely motivated by the combined geopolitical and economic goals of determining the location of the Spice Islands and breaking the Portuguese monopoly solidified only some 10 years earlier. The expedition began on 10 August 1519 as five ships with a combined crew of 234 left Seville for San Lucar de Barrameda; 5 weeks later, on 20 September 1519, they sailed (Table 1).

Table 1. Magellan's expedition.

Ship	Tonnage	Crew	Disposition
Trinidad	110	55	Captured by the Portuguese while trying to return via the Pacific
San Antonio	120	60	Turned back during passage through the Straits
Conception	90	45	Abandoned in fall 1521 in the Spice Islands (Moluccas)
Victoria	85	42	Reached Spain on 6 September 1522
Santiago	75	32	Wrecked on Argentine coast during southern winter
Totals	480	234	

The Magellan Voyage experienced two mutinies early on, one before and one after reaching the South American coast. On 28 November 1520, three remaining ships reached the Pacific Ocean through the Straits of Magellan. Following arrival at the Spice Islands on 6 November 1521 with 115 crew left, Magellan was killed by locals before the remnant of the expedition left for home. On 6 May 1522, *Victoria* rounded the Cape of Good Hope under the command of Juan Sebastian de Elcano. Twenty of the crew died of starvation before reaching the Cape Verde Islands and another 13 were abandoned there on 9 July (Cape Verde was a Portuguese holding). Eighteen men returned on the *Victoria* to Seville in 1522; 4 of the original 55 on the *Trinidad* reached Spain in 1525. The voyage had covered 14,460 leagues (69,000 km)

The *Victoria* reached Spain 1 day early despite maintaining a careful log; it had gained a day by traveling west. Despite the loss of four of the five ships, the return of 26 tons of cloves along with nutmeg, mace, cinnamon, and sandalwood covered the expedition cost.

The cargoes were sufficiently valuable per weight that voyages of Portuguese, Dutch, British, and American traders continued. Fortunes and empires were made and lost, but the stakeholders of the next three centuries saw the potential gains as outweighing the risk and upfront costs.[19,20]

"Small Wars"

With respect to Von Braun's assertion that the cost of a Mars mission would be comparable to that of a small war, a comparison of the financial costs of major U.S. wars allows such an assertion to be put into perspective (Table 2).[21]

Von Braun's initial assertion of the cost of a Mars expedition lies between the financial outlays of the U.S. government for the Mexican War (1846–1848) and the Spanish-American War of 1898. The effects of these events can be seen more clearly in Fig. 4.[22,23] Spikes in the federal and defense budgets indicate the two World Wars; smaller localized increases indicate the Korean and Vietnam conflicts. The large relative peak in the NASA budget is from the Apollo program (and the other programs supporting the manned lunar missions).

Downsizing the Architecture

On 11 July 1962, NASA announced the lunar orbit rendezvous approach for getting men to the surface of

Table 2. U.S. war costs in fixed 1990 dollars.

Conflict	Cost (billions $)	Cost per capita
Revolutionary War	1.2	342.86
War of 1812	0.7	92.11
Mexican War	1.1	52.13
Civil War	44.4	1,294.46
Spanish-American War	6.3	84.45
World War I	196.5	1,911.48
World War II	2,091.3	15,665.17
Korea	263.9	1,739.62
Vietnam	346.7	1,692.04
Gulf War	61.1	235.00

the Moon. This had the risk of rendezvous and docking in lunar orbit but required the lowest lunar spacecraft weight, and only one Saturn launch vehicle was needed per flight. Hence, this was the cheapest, fastest way to get to the Moon. It eliminated the need for the larger Nova launch vehicle, for any Earth-orbital assembly, and for a man-rated nuclear rocket. To the extent that any such components would be needed for a human mission to Mars, their development would have to come anew from a Mars-specific program.

Work continued on Mars mission concepts based on Apollo hardware and, in particular, multiple Saturn V launch vehicles for moving the hardware into orbit. With the Mariner 4 flyby of Mars and the measurements of atmospheric pressure, all notions of aerodynamic landings such as used in the Von Braun scheme vanished, as did all notions of the possible presence of advanced life on Mars.[4]

In January 1966 the National Academy of Sciences Space Studies Board issued its report, *Space Research: Directions for the Future,* targeting "the near planets" for scientific focus following the manned lunar landing. As a result, the significant robotic mission, Voyager—first proposed at the Jet Propulsion Laboratory in 1960 as a follow-on to the Mariner flyby missions and designed to use the Saturn V launch vehicle—was reassessed. The new atmospheric data drove a redesign and increased program costs, but launches were scheduled for 1971 and 1973.[4]

Within 2 years, the Mars Voyager missions were cancelled and replaced with the Viking orbiters and landers that subsequently flew to Mars. By 1973, the post-Apollo program for manned exploration beyond Earth orbit had collapsed, along with the nuclear rocket development program. Plans for any future uses of the Saturn V were shelved, and development of the Space Shuttle began as a new initiative.

Over the next 30 years, plans for manned Mars missions continued to be studied, notably including the National Commission on Space Report of 1986, with priorities reset by the Ride report following the loss of the Space Shuttle Challenger; the Space Exploration Initiative of 1989; and the Design Reference Mission (DRM) of 1997.[4] Almost all conceivable architectures were advocated in these and other studies, which required masses in LEO (sometimes referred to as "initial mass in low-Earth orbit," or IMLEO) of hundreds of tons and estimated costs ranging from tens to hundreds of billions of dollars.[4]

In each case the combined cost of infrastructure and implementation was seen as prohibitive, and the programs were not started. Whether the new exploration initiative[24] will fare any better remains to be seen.[2,25]

While there have been some reports on what a manned mission to destinations farther from Earth than Mars would require—notably very advanced propulsion systems[26]—the goal of Mars has been the focus of all "near-term" thinking. Here we take a more global view of the drivers for solar system exploration, the requirements that follow, and how the overall task can be divided into coherent synergistic robotic and human components.

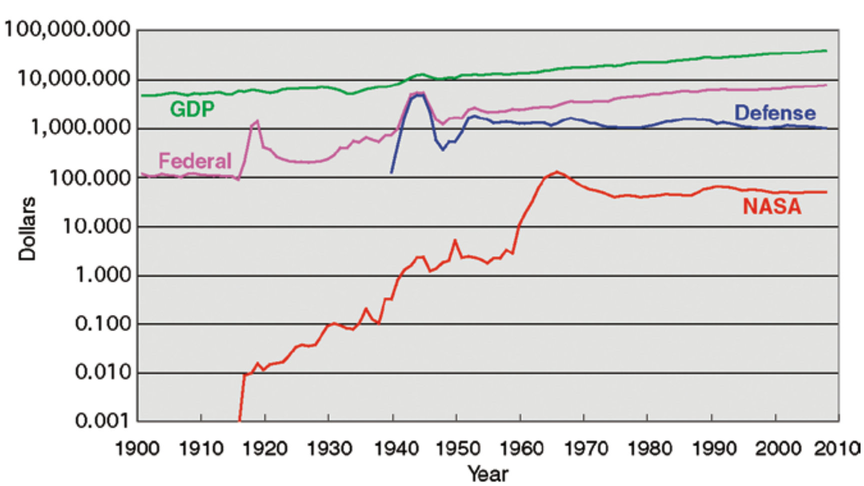

Figure 4. Comparison of fixed-year (1996) costs per capita. National Advisory Committee on Aeronautics (NACA) and NASA budgets on a per capita basis are combined. The NACA budget is for the years 1915–1959; NASA was formed in 1959. All budgets are based on actual figures from 1901 or later until 2002, and projections are from 2003–2008.

An Antarctic Paradigm?

Discovery and Exploration

While the drivers behind Magellan's voyage do not appear to be strictly applicable to Mars, the exploration of Antarctica and establishment of scientific bases there may have more relevance. The Antarctic continent was discovered only relatively recently in 1820. Initial expeditions were all privately funded, including Amundsen's successful traverse to the South Pole in 1911 and Byrd's establishment of his Little America bases up through Little America III during his 1939–1941 expedition.[27,28]

Highjump

Even with a growing commercial whaling and fishing competition off the shores of Antarctica, the modern history of the continent began for political reasons following the end of World War II. The United States commenced operations of Task Force 68 in 1946–1947. The context was the disputed claims of Argentina and Britain during World War II and growing interests in the possible exploitation of natural resources following the war by a variety of governments.

With then-Admiral Byrd in command, Operation Highjump established the Little America IV base involving 13 ships, 33 aircraft, and 4700 men. Larger than all previous expeditions combined, the operations surveyed ≈350,000 mi^2 of the continent and photographed ≈60% of its coast.

Deep Freeze

Highjump was followed by Operation Deep Freeze I in 1955, laying much of the groundwork for U.S. participation in the IGY. That effort involved 12 countries establishing some 40 scientific bases, and led to the development of the Antarctic treaty governing treatment of the continent and its uses as a multinational scientific exploration site. This work continues to this day. The IGY marked the start of the first permanent bases on the continent—some 137 years after its discovery.

Logistics

U.S. costs for sustaining the Antarctic research bases, infrastructure, and facilities have grown from ≈$150 million/year at the time of the IGY up to a current spending level of ≈$200 million/year.[28]

To support Antarctic operations, both people and cargo must be moved in and out. In the 1990–1991 Deep Freeze operation, ≈7200 MT of cargo were transported (ship and air, intercontinental and intracontinental) and 6200 personnel were transported by air (intercontinental and intracontinental).[29]

If we extrapolate over a 46-year period, the total mass is ≈330,000 tons—the mass of the Empire State Building—a rough estimate of resources transported into and out of the continent. Looking at large masses that have been transported by air, the Berlin Airlift transported 2.1 million MT (slightly less than half the mass of the Great Pyramid of Giza) over 14 months with ≈280,000 airplane flights. This was a major undertaking, but the point is that it was not impossible.[27]

With all of the constraints of costs and the terms of the Antarctic Treaty, *in situ* resource utilization has not been a viable approach for providing needed resources for the bases, e.g., fuel for transport and electrical power. Even at these relatively large amounts of cargo that must be shipped in, the "break-even" point for using local resources in Antarctica has not been reached.

Extreme Engineering Limits?

Before contemplating large masses of materials in space for eventual use, e.g., for deep-space human exploration and our establishment of permanently crewed bases, it is worth inquiring about the scale of large engineering projects. To give an idea of scale, Table 3 lists projects and items that have been built and Table 4 lists others that have been contemplated. The largest deep-space vehicle built and flown is the ≈30-MT Apollo system, less than 1/1000 the mass of Von Braun's original Mars expedition concept. In these examples human capabilities and imagination span some 9 orders of magnitude for "extreme engineering."

STRATEGY AND REQUIREMENTS

"If you can fill the unforgiving minute / With sixty seconds worth of distance run, / Yours is the Earth and everything that's in it. . . ."[49]

R. Kipling

The Previous NASA Strategic Plan

The NASA Strategic Plan of 2003[50] posed three compelling questions that drive exploration: (1) How did we get here? (2) Where are we going? (3) Are we alone? As an actionable goal, these questions broadly map into Mission II: To explore the Universe and search for life, and, in turn, to Goal 5: Explore the solar system and the Universe beyond, understand the origin and evolution of life, and search for evidence of life elsewhere.

This approach, largely endorsed by the scientific community in the recent decadal study on solar system exploration goals, focuses on understanding the origin of the conditions for life on Earth and possible origins of life elsewhere in the solar system. Emphasis has been on sites with water and suspected prebiotic chemistry, namely, Mars, Europa, and Titan.

For all of these primary targets, as well as other targets of exploration, the issue is always one of timely return of conclusive scientific data. For robotic missions, "timely" can be from 1 year for reaching Mars orbit, to almost 10 years for the Huygens probe into Titan's atmosphere, to even multiple decades for the Voyager spacecraft traveling to the interstellar medium. Scientists can be patient; "reasonable" timescales are set by the design lifetime for spacecraft components and budgets, for mission operations, and for the science teams as they await the data.

Table 3. Extreme engineering: What we have built.

Item	Type	Mass (tons)
Great Wall of China[30]	Structure	730,000,000 (est.)[a]
Hoover Dam[31]	Structure	6,600,000
Golden Gate Bridge[32]	Bridge	811,500
Jahre Viking[33]	Ship	647,955[b]
Empire State Building[34]	Building	365,000
Nimitz-class aircraft carriers[35]	Ship	102,000
Ohio-class submarines[36]	Ship	16,600
Eiffel Tower[37]	Structure	10,000
Saturn V[38]	Rocket	3,038.5[c]
An-225 Cossack[39]	Cargo plane	600
Statue of Liberty[40]	Structure	225
Apollo 17[38]	Crewed spacecraft	30.34[d]
Cassini[41]	Robotic spacecraft	5.65[e]

[a]Mass of the Great Wall is estimated from a density of 2.0 g cm^{-3}, a length of 7300 km, an average height of 10 m, and an average width of 5 m.

[b]*Jahre Viking* is the largest ultra-large crude carrier (tanker) currently in maritime service.

[c]Saturn V mass at launch is the mass as fully fueled before launch.

[d]Apollo 17 mass is the mass injected from Earth to the Moon.

[e]Cassini mass is the total mass launched to Saturn before any trajectory correction maneuvers or injection into Saturn orbit.

Table 4. Extreme engineering: What we have thought about building.

Item	Type	Mass (tons)
Interstellar photon rocket[42]	Crewed spacecraft	2,301,000,000[a]
L5 space habitat (10,000 pop.)[43]	Structure	10,618,000
Das Marsprojekt propellant[5]	Propellant	5,303,850
Das Marsprojekt vehicles[5]	Crewed spacecraft	37,200
ROOST[b] post-Nova LV[44]	Launch vehicle	16,980
Saturn V-D[c] concept[45]	Launch vehicle	9,882.1
Jupiter/Saturn fusion ship[26]	Crewed spacecraft	1,690
Completed International Space Station[46]	Structure	453.6
TAU-probe[d] (interstellar)[47]	Robotic spacecraft	61.5
RISE probe[e] (interstellar)[48]	Robotic spacecraft	1.1

[a]The photon rocket was based on a round-trip at 1 *g* acceleration to Alpha Centauri using total matter annihilation for thrust.

[b]ROOST = Reusable One Stage Orbital Space Truck.

[c]Saturn V-D concept was from a Marshall Space Flight Center study of 1968.

[d]TAU = Thousand Astronomical Units mission.

[e]RISE = Realistic Interstellar Probe.

"The Vision for Space Exploration"

On 14 January 2004, President Bush espoused a new vision for NASA,[24] which has four points:

1. Implement a sustained and affordable human and robotic program to explore the solar system and beyond
2. Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations
3. Develop the innovative technologies, knowledge, and infrastructures to explore and support decisions about the destinations for human exploration
4. Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests

If the logical extension of point 2 is to be considered seriously, and if all stakeholders, both those of the new vision and those of the old plan, are to come together to further space exploration, then a comprehensive plan for the exploration of the solar system—or at least a framework for one—is needed.

Key issues are the sustainability and public engagement of the effort over a space of decades, especially where this is an act of public policy and not a war for survival. Underlying these issues are assumptions that will motivate the expenditure of funds required for this activity.

Access to Space

"Once you get to earth orbit, you're halfway to anywhere in the solar system."[51]

R. A. Heinlein

If the new initiative is to be sustained as was the Antarctic program and not like a short-term program such as Apollo—and if humans are to be a major player in deep space—then one thing is clear: we must be able to move a lot of mass reliably, efficiently, and cheaply from the Earth's surface into orbit. Once free of Earth's gravity, appropriate vehicles can be deployed (e.g., Apollo) or built (e.g., Von Braun's Mars vehicles), but we will need capabilities well past those of the Space Shuttle without the high costs.

Costs of access to space can already be decreased if sufficient up-front orders are placed. If the architecture requires 20,000 MT in LEO, an order for 1000 heavy lift launch vehicles (HLLVs) with a capability of 20 MT to LEO will come in at a lower unit cost than will an order for 10.

If payloads to LEO come in units of 1000 MT, then a new class of launch vehicle should be considered. Before the Lunar Orbit Rendezvous technique was adopted for Apollo, "million pound to LEO" vehicles (generically called Nova) were studied in the early 1960s.[44,52] If we are serious about taking humans to Mars and beyond, this old idea should be considered in the guise of a new class of launch vehicle.

Extremely heavy lift launch vehicles (EHLLVs) could extend the Nova concept: take 1–5 million lb (454–2270 MT) to LEO. Such vehicles would be very large and hence inherently expensive, so reusability would be required to be economical, an idea studied in, e.g., Reusable Orbital Module-Booster and Utility Shuttle (ROMBUS).

Development costs would also be very large, but such vehicles could solve the access-to-space problem for transporting infrastructure to the Moon and beyond. Recalling the Antarctic example, suppose that ≈7,200 MT of cargo was required to be shipped to Mars each year. To transport 600 MT of cargo to Mars orbit, Von Braun needed 37,000 MT in LEO. Getting 7,200 MT of supplies (whatever they are) to Mars orbit (and still not to the surface), would likely need ≈300,000 MT in LEO. With a 2,000-MT to LEO EHLLV, the transport could be done with 150 flights in about a year at three flights a week. Such an undertaking would be neither cheap nor easy, but it could be done. Both in leaving Earth and traveling to other destinations, propulsion is the key issue.

"Difficult" Robotic Missions

The same missions that were "difficult" in the NASA 1976 Outlook for Space Study[53] remain difficult today, primarily, but not exclusively, because of the propulsion requirements. A sample return mission from Mars is just doable with current technology, providing one is willing to pay the price. Sample returns from Mercury and Venus need high thrust to deal with descent (at Mercury) and ascent (at both). In addition, round-trip travel to Mercury is prohibitively long if chemical systems are used.[54]

Titan orbiters, Uranus and Neptune system probes (similar to Galileo at Jupiter and Cassini at Saturn), have also "been on the books" for almost 30 years. These have been joined by newer mission concepts such as Europa landers and submarines and Io orbiters that also lie at or beyond current (chemical) propulsive capabilities.

The propulsive difficulties are generic. To go to the outer solar system to any body and into orbit with a capable science payload requires much higher specific impulse to be implemented, but can also be low thrust (but not too low). To land on any solid—and airless—body from Mercury to Pluto requires high thrust at the target as well, and hence more mass. The problem is further exacerbated if a sample is to be returned to Earth.

Depending on the body, potential destinations can be arranged into four groups as a function of their escape velocity, indicative of the amount of high-thrust propulsive capacity required (objects in Table 5 are listed in order of increasing distance from the Sun and in increasing distance from the central planetary body in each system).

NASA's Project Prometheus was a first step toward trying to solve these transportation difficulties. The first planned mission, the Jupiter Icy Moons Orbiter (JIMO),[55] was to use a nuclear electric propulsion system powered by a fission reactor to address science goals in the Jovian system that cannot be addressed otherwise with a single mission. Science goals include the deduction of internal structure and the possible presence of liquid water beneath the ice crusts of these worlds. A June 2003 NASA workshop identified 8 science areas, 33 objectives, and 102 investigations requiring 188 different types of measurements. The main question is cost: reactor + certification! + spacecraft + instruments/science.

Table 5. Escape velocities for some objects.

Group	Object	Escape speed (km/s)
1	Earth	11.18
	Venus	10.36
2	Mars	5.02
	Mercury	4.25
3	Moon	2.38
	Io	2.56
	Europa	2.02
	Ganymede	2.74
	Callisto	2.44
4	Rhea	0.64
3	Titan	2.64
4	Titania	0.77
	Triton	1.45
	Pluto	≈1.20

The Role of Humans (Do We Need Astronauts?)

Robotic missions can be summarized as follows: Launch a probe to a target and the probe returns knowledge. The problem is that without return of all the data, there are always lingering doubts about how the knowledge is to be validated ("compression" leaves doubts of data fidelity). Return of all data requires large bandwidth which, in turn, drives receiver and transmitter sizes and transmitter power. Thus data return drives power and hence mass, which in turn drives propulsion. Even with all the data returned, doubt can still linger about whether we really—and correctly—thought through all of the contingencies and possibilities ahead of time.

Having humans in the loop can make a large difference. An obvious example is the hand-selected Moon rocks returned by astronaut/geologist Schmidt on Apollo 17 versus the ≈100 g of lunar material returned by the robotic Luna 24 probe. However, if one also considers the cost differential of the two missions, one immediately reaches two conclusions: (1) sending astronauts beyond Earth orbit is really expensive, and (2) one gets what one pays for. So there is a role for humans, but it will not come cheaply. While eventual human missions to Mars are an assumption of the exploration vision, it is relevant to ask whether it is desirable—or even doable—to take human missions beyond Mars, farther into the solar system.[26]

The Requirements

Sample return missions, or human missions (which also involve a return), have significantly harder propulsive requirements than those of a simple, fast flyby mission. Such missions must stop at the target, reverse direction, and again stop at Earth. If the top speed in both directions is the same as that of a fast flyby (and assuming the time to accelerate is small compared to the transit time), the trip time is double that of a fast flyby, but the propulsion requirement is quadrupled. If we take ≈50 astronomical units (AU) as the characteristic outer size of the solar system (the heliocentric distance to Pluto from the Sun near its aphelion in the year 2113 as well as the distance to most of the distant Kuiper Belt objects seen to date), then the required mission time sets the required propulsive capability for accessing the farthest part of the solar system.

As an example, consider a round-trip time of 4 years. With a human crew, such a maximum mission duration (longer than Magellan's voyage!) would still be long and perhaps unacceptable from both psychological as well as radiation exposure aspects. In addition, without a true 100% enclosed ecosystem, the mass of food, oxygen, and water for the crew increases with mission time. To continue with the example, to traverse the solar system in 4 years (round-trip) requires a 2-year voyage to Pluto and the same duration back. In turn, this constraint requires accelerating to ≈25 AU/year and then decelerating by the same amount at the destination. The return voyage would require the same performance, for a total onboard capability of 4 × 25 AU/year = 100 AU/year or ≈500 km/s of delta-*V*. The corresponding specific impulse is ≈51,000 s and significantly exceeds even nuclear thermal rocket capabilities. Without practical controlled fusion, such a voyage could only be contemplated with a nuclear electric propulsion (NEP) system of a very advanced design.

This conceptual approach can provide a quick but reliable estimate of the implied propulsion system requirements. Backing requirements off to shorter distances or longer times yields less required propulsion capability. A sample return mission to Pluto near aphelion that required 40 years to bring a sample back would require a total delta-*V* capability of "only" 4 × (50 AU/20 years) = 10 AU/year or ≈50 km/s. Similarly, a crewed mission to the Jupiter system at 5 AU with a round-trip time of 4 years would also require a delta-*V* capability of 4 × (5 AU/2 years) = 10 AU/year or ≈50 km/s, assuming that the acceleration time is short compared to the cruise time. For example, a constant acceleration of 0.001 *g* would build up to 12.5 km/s in about 15 days. Reaching 125 km/s would require 150 days at the same acceleration.

The primary difference between crewed and robotic missions is mass, the other driving requirement for human missions. Even in comparing a sample return mission with the same timescale for mission completion, mass and its associated cost remains the principal driver. For example, the Soviet lunar sample return missions—Luna 16, 20, and 24—had masses of 5600, 5600, and 4800 kg, respectively. In contrast, the Apollo spacecraft at trans-lunar injection had a capability for a mass of ≈48,000 kg, about 10 times as much for the sample return missions. The Viking 1 and 2 spacecraft had masses of 3399 kg. This can be contrasted with NASA's crewed DRM Mars mission of 1997 that required an initial 303 tons.[4] This was a scrubbed version of the DRM of 1993 that took six astronauts to Mars for a 2.5-year mission, including a 600-day stay and requiring ≈380 tons (including the propellant, but with some offset from the manufacture of some fuel stock on Mars). In any case, about 100 times the mass initially in LEO is required (for a Mars mission at least) for a crewed round-trip mission versus a robotic lander (the twin Spirit and Opportunity rovers had masses of ≈830 kg). These numbers are also significantly less than the 40,000 tons in orbit required for the initial Von Braun concept.

Power Consumption

The implied mass and required delta-*V* translate into substantial in-space power requirements for a spacecraft. Again, some simple estimates can provide insight into the capability and characteristics for the required power plant.

The high specific impulse required (to keep the propellant mass tractable) already rules out the use of chemical or even nuclear fission thermal rocket engines. Suppose the total delta-V capability is 50 km/s with a total "burn time" of 4 × 150 days, i.e., ≈1.6 years, at a constant mass flow rate. Suppose also that the initial propellant mass fraction is 60%, translating into a mass ratio of 2.5 and a required exhaust speed of ≈55 km/s (specific impulse of ≈5600 s). For a 3000-kg spacecraft, the initial propellant load would be 1800 kg. If this amount were to be processed over 600 days, the required mass flow rate would be 3 kg/day or ≈35 mg/s. The implied exhaust power is 51.7 kW, and acceleration is in the tens to hundreds of microgees. For a prime power conversion efficiency of 20% using an NEP system, the reactor thermal power would need to be ≈260 kW. These parameters are close to specifications for the reactor concepts studied for the JIMO spacecraft under Project Prometheus.

The need for a "mass-efficient" power source is exacerbated when a human crew is considered. For a crewed expedition of ≈300 MT, and the same scalings, the power consumption required is increased by the increased mass flow rate, a factor of 100 to ≈5.2 MWe (megawatts electric), with a thermal reactor power output of ≈26 MW, consistent with Stuhlinger's NEP system designs[56,57] of the 1960s. For either of these cases, an efficient vehicle should have a power plant specific mass α of $\approx \tau / v^2_{exhaust}$ as derived by Stuhlinger, where $v_{exhaust}$ is just the exhaust speed of the propellant and τ is the acceleration time. In these cases, α = ≈17.5 kg/kWe, implying a power supply of ≈905 kg out of 1200 kg dry and 90 MT out of 120 MT, respectively.[58]

For a far-ranging mission with the same propellant burn time (300 days out of a cruise leg of 2 years) and an initial mass of 300 tons but with a total delta-V of 500 km/s, the exhaust speed would need to increase by a factor of ≈10 for efficient propellant use. But in keeping the power plant working efficiently, the power plant specific mass would need to decrease by a factor of 100 for the same "burn" time. "Low-thrust" missions throughout the solar system are certainly possible for sufficiently long durations, but the simultaneous implementation of short mission times is problematic with currently foreseeable technology.

Human missions to the Jovian system may not be totally crazy, but are certainly not easy, and are far more difficult than a human mission to Mars. Human missions to more distant destinations will be even more difficult—and certainly more massive.

A PLAN FOR THE FUTURE

"If you can keep your head when all about you / Are losing theirs and blaming it on you."[49]

R. Kipling

"The greatest gain from space travel consists in the extension of our knowledge. In a hundred years this newly won knowledge will pay huge and unexpected dividends."[59]

W. Von Braun

To discuss future possibilities, one has to make many trials with the knowledge that most, if not all of them, will miss the mark. Where we currently are includes a robust robotic program at Mars, a new probe to Mercury, an ongoing program to reach Pluto robotically, and a stalled human program. Future plans show promise for enhancing robotic missions with NEP and a vision for taking the human race beyond Earth orbit and staying there this time. The past has shown us that the robots will come first. If we combine this principle with the goal of expanding the human presence throughout the solar system during the next 100 years, then a structure for doing so can be imagined that starts with sample returns and ends with permanent bases and expansion into the outer solar system (Table 6). Underlying all of these possibilities is the assumption that easy access to space for large masses is available to develop self-sustaining infrastructure off Earth.

In the meantime, we need to keep exploring with a diversity of missions to enable all levels of scientific enquiry. Pluto will be at aphelion about 2113; we must decide whether we will be there as well. It really is up to us.

Table 6. A future exploration plan: Selected milestones (notional).

Year	Goal
2011	Juno launch to Jupiter
2015	Interstellar Precursor Mission launch ("Interstellar Probe")
2016	Europa Geophysical Explorer launch
2020	Human launch to L2 to service James Webb Space Telescope
2023	Mars Sample Return (robotic) mission launch
2025	Crewed expedition to a near-Earth object to demonstrate hazard mitigation
2025	Launch of a robotic tour to the Neptune system
2030	Permanently staffed lunar base
2030	Human mission to Mars
2035	Launch of robotic sample-return missions to the outer solar system
2050	Human mission to Callisto (Jupiter system)
2075	Human mission to Enceladus (Saturn system)
2080	Permanent Mars base establishment
2090	Human mission to Triton (Neptune system)

CONCLUSION AND PERSPECTIVE

"*And pluck till time and times are done / The silver apples of the moon, / The golden apples of the sun.*"[60]

W. B. Yeats

Although crewed missions beyond the main asteroid belt may remain problematic (if even desirable) throughout this century, major scientific questions remain that can only be answered by going there, a situation that has not changed during the last 30 years.[6,54] Enigmatic Europa may contain even more clues than Mars about the evolution of life in the Universe, yet actually remotely probing beneath that moon's icy crust will likely be as difficult as landing a field geologist on the Martian surface. The entire solar system must be considered as part of the ultimate Vision if it is to take fire and go forward.

A new perspective is required. Here we are talking about a program that will last for decades and will—at some point—require large capital pieces of equipment. Again, the analogy of permanent science stations in Antarctica comes to mind. For the solar system to become our extended home, the effort involved must become "obvious" to the public and politicians alike as a long-term goal in the national interest. Only in this way can progress be maintained toward the consolidation of the solar system during the next century.

To continue moving outward, significant new developments will be required, all enabled by and requiring new advances in propulsion. Top-level elements and requirements include communications infrastructure, modular hardware that is evolvable and scalable (not unlike Airbus or Boeing airliners), a CEV for multiple uses, and minimum buys of large numbers of evolved, expendable LVs to keep unit costs—and the cost of access to space—down. In addition, there is a need for cargo-capable HLLVs (or larger EHLLVs) to push past Apollo-like tasks on the Moon and prepare the way for Mars. There will be roles for the L2 Lagrange point, both as a way-station for our solar system and as a location for observatories of other star systems. Automated CEVs wed to advanced Prometheus vehicles for outer solar system exploration and sample returns will also have their place.

The current goal is to answer fundamental questions about our origins and the origins of life in this system, but there will always be a need for a clear, yet evolving, concept of where we can ultimately go—if we want to.

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