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SOLAR SYSTEM EXPLORATION: A VISION FOR THE NEXT HUNDRED YEARS

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ABSTRACT

The current challenge of space travel is multi-tiered. It includes continuing the robotic assay of the solar system while pressing the human frontier beyond cislunar space, with Mars as an obvious destination. The primary challenge is propulsion. For human voyages beyond Mars (and perhaps to Mars), the refinement of nuclear fission as a power source and propulsive means will likely set the limits to optimal deep space propulsion for the foreseeable future. Costs, driven largely by access to space, 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, the needed technology, initial capital investments, and markets have continued to fail to materialize. Hence, initial development in deep space will likely remain government sponsored and driven by scientific goals linked to national prestige and perceived security issues. Against this backdrop, we consider 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 AU 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."
– Proverbs, 29:18[1]

There is a great deal of new interest in space and space travel with the recent (Feb. 2004) publication of the Aldridge Commission Report[2], efforts on developing current space tourism, and the ongoing series of missions to provide scientific exploration (notably of Mercury, Mars, Saturn, and Pluto). NASA undergoes a "road mapping" activity on three-year centers that feed into the overall Agency Strategic Plans, and this type of planning has been extended in the recent 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 – that policy goals and technologies will change so radically on longer time scales 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 look at what people thought might happen in the previous hundred years, what really did happen – and why, and, perhaps more to the point, what it cost.

Especially following the technical gains in rocketry and atomic power brought about by the second world war, there was a great deal of speculation of 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 of manned flights to earth orbit and beyond. While that outlook gave way to robotic probes always going to a destination first, it has always, at least to the majority of people, been with the idea that eventually humans would follow.

The Art of Prediction

Future predictions can, and many times, are misleading. An example is the prediction from the early days of the automobile that it would be soon 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 ferry vehicles for carrying 39.4 metric tons 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 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-metric ton vehicle that can carry 24.4 metric tons to a 204-km orbit. The Shuttle has better performance but with less cargo because a realistic altitude is higher than Von Braun envisioned. Von Braun also envisioned the driving cost for his Mars mission being the $500M for 5,303,850 metric tons of propellant for the ferry ships to transport propellant and supplies to Earth orbit (this translates to ~$3.6B FY96$) during the 950 flights by 46 vessels in eight months (one 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 give some 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

For any mission there are 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 reason for going for the Apollo missions was the geopolitical situation while the reason for going for robotic missions has been a combination of supporting Apollo goals (early on), science mixed with geopolitics (the U.S. 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 significantly grew from the V-2 work of World War II and later intercontinental ballistic missile (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 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 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. Typically new missions have significant new technologies that require implementation (and sometimes

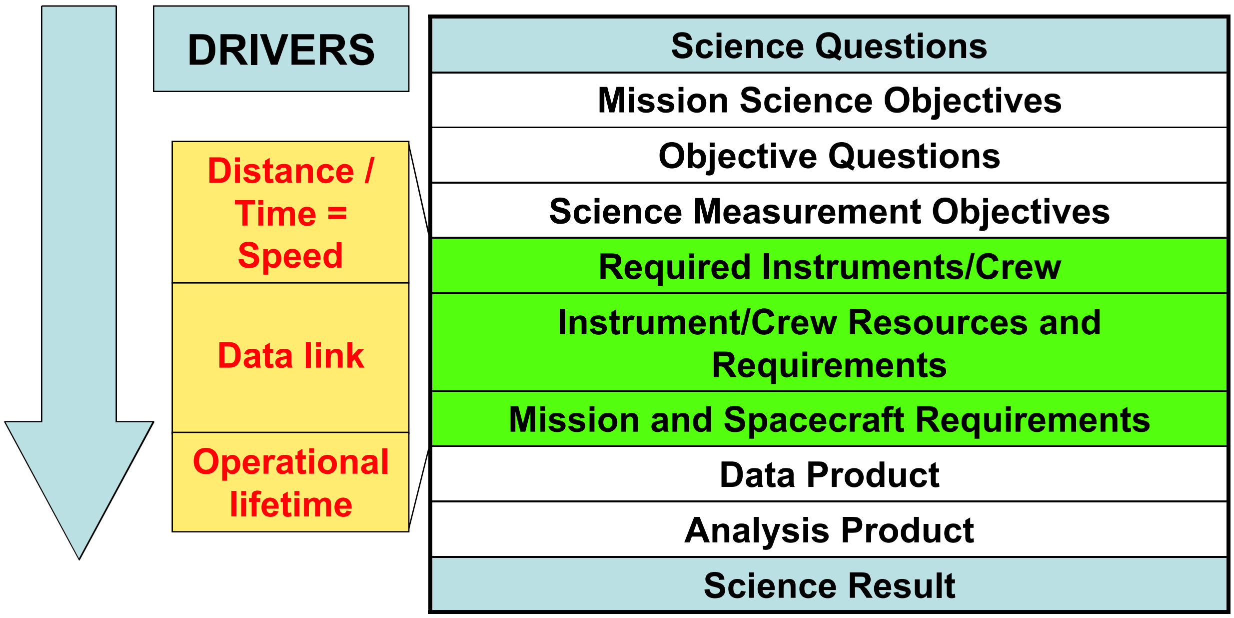

FIG. 1: Answering solar system science questions is a "system of systems" problem.

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 principal 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 capable of providing results that answer the posed questions. Demonstration of such closure (at least in principle) is part of the strategy that must be developed up front (Figure 1). The global requirements that drive the mission design, implementing technologies, and especially cost include: (1) how far are we going, how long can we take, is this a flyby, rendezvous, or return mission, i.e. what total velocity change capability is required, (2) what are the data link requirements, bandwidth, coverage continuity, and (3) what is the required operational lifetime – driven by both point (1) and reserve requirements – and including hardware, autonomy, sparing philosophy, and consumables, both for the mission and for a human crew, if there is one.

THE PAST

"Those who cannot remember the past are condemned to repeat it." – G. Santayana[7]

Beginnings

The conquest of the solar system has been a favorite theme of science fiction writers for well over a hundred 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 Tsiolkovskii, Oberth, and Goddard laid 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 the Second World War 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 Intercontinental Ballistic Missiles (ICBMs), and later in the development of the launch vehicles currently in use for manned, commercial, and scientific exploration purposes.

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 seen 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] notes 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[13, 14]

Beginning with Sputnik I in October 1957 and going through calendar year 1998, there have been 3973 successful space launches, the majority of which 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 the current calendar year, there have been only 139, or which 112 have been successful. Thus less than 3% of all space missions launched to date have gone beyond Earth orbit (Figure 2).

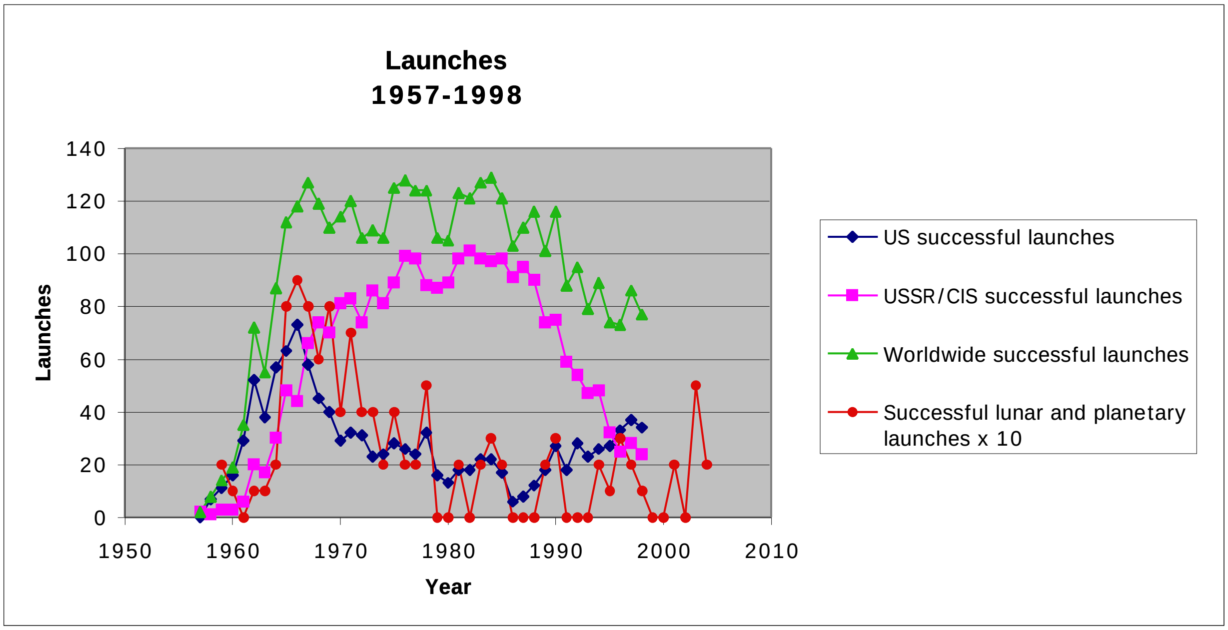

FIG. 2: Historical launches from 1957 to 1998. Successful interplanetary launches through 2004 have been added from NASA websites. All launches, including the percentage that were beyond Earth orbit continued to grow until about 1965 when the number of U.S. launches began to taper off. The downturn in Russian launches coincides with the end of the Cold War era. Lunar and interplanetary launches include all countries. Following a peak in the mid-1960s, they have tapered off to 10% or less of the U.S. only launches.

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 place in orbit in January 1958. In the U.S. the National Aeronautics and Space Administration (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 Figure 2[13,14]. Historically (in the U.S. at least), focus on the Moon (Ranger, Surveyor, Lunar Orbiter) and early interplanetary probes (Pioneer 5-9 to measure interplanetary radiation) supported the manned lunar landing effort announced by President Kennedy in May 1961. Both the U.S. and 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. Pioneer 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 perhaps its interaction with the very local interstellar medium (VLISM).

Voyager results motivated a desire for more in-depth study of the outer solar system. Detailed study of the Jovian system was provided by the recently completed Galileo mission. Such studies of the Saturnian system are just now commencing with the Cassini/Huygens mission, a joint effort by NASA and the European Space Agency (ESA).

Venus. Venus exploration can be split into orbital missions that probed the space environment of the planet and used radar to penetrate the permanent clod deck and landers that gave brief spot measurements of conditions at the surface. From the mid-1960's to the mid-1980's the then-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 the planet 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 off the planet Mercury).

Orbital studies by Pioneer 12 (also Pioneer Venus Orbiter or PVO), atmosphere studies by Pioneer 13 (also Pioneer Venus Multiprobes), and radar studies by PVO and then the Magellan spacecraft in the 1990s have completed Venus investigations to date. Venus Express, an ESA mission based upon the successful Mars Express spacecraft, is to return to Venus in the near future.

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 measurements of a very low atmospheric pressure. More data were accumulated by the U.S. Mariner 6,7, and 9 spacecraft and by the Soviet Mars 2-7 probes.

An all-out effort was made by the U.S. to determine whether life existed on Mars with the Viking 1 and 2 missions that consisted of orbiters that 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 (RTGs). While the changing of the Martian seasons were 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 Mars Global Surveyor orbiter (NASA – still operating in extended mission), successful mission include the NASA Mars Pathfinder rover mission (second of NASA's Discovery line of missions), NASA's 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 well as evinced by the failures of Nozomi (Japanese Space Agency), Mars Climate Observer, Mars Polar Lander, Deep Space 2 (all NASA), and Beagle 2 (ESA/UK lander).

Capacity for Future Growth

Whether financed by governments or by private interests, space exploration is an expensive undertaking. 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.

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 this time, this reconstruction of financial activity shows a gross domestic product (GDP) in fixed-year (1996) dollars increasing from ~\$4 billion to ~\$9,400B as the population grew from ~3.8 million to ~280 million people, yielding a GDP per capita increase of a factor ~30 over ~200 years. The economy exhibits an e-folding time of ~30 years that has yet to show signs of decelerating.

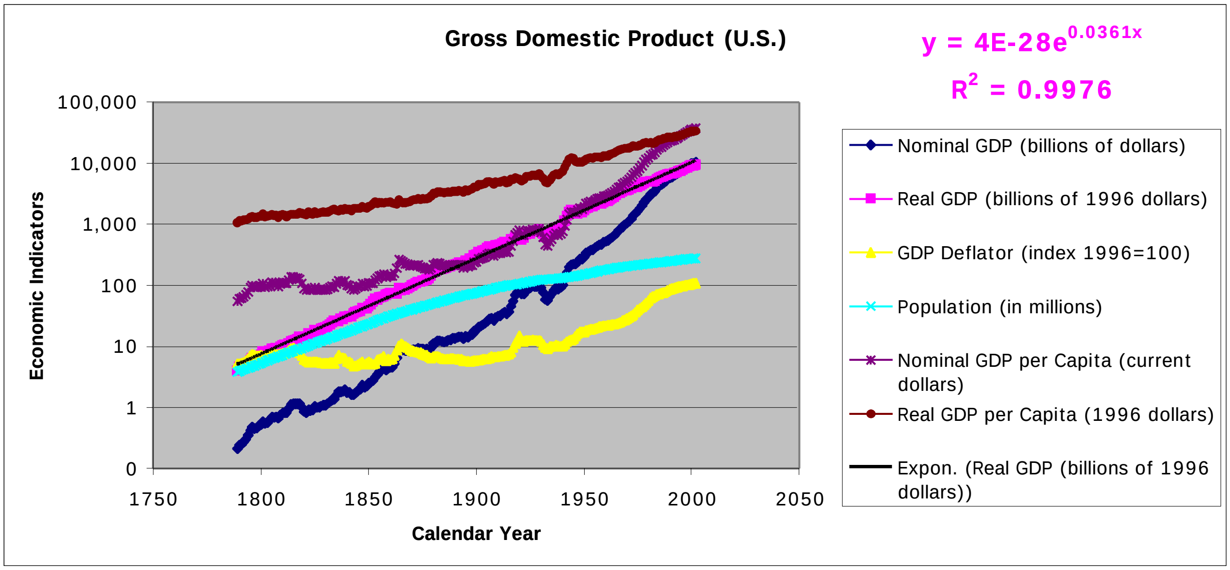

FIG. 3: U.S. economic and population trends 1789-2002[17]. The GDP in fixed-year dollars shows an e-folding time of ~28 years.

While 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

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

Das Marsprojekt. The first detailed study for 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 with a total crew of 70 assembled in Earth orbit with ten crew per manned ship and three cargo ships. Nine hundred and fifty 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 upon nearer term chemical technology in which case there was a need of 5,320,000 tons of propellant to assemble (and fuel) the Mars ships. The author noted that "about 10 per cent of an equivalent quantity of high octane aviation gasoline was burned during the six months' operation of the Berlin Airlift" in 1948-1949. Estimated total cost for launching the mission into Earth orbit as $500 million (now over $3B as noted in the introduction).

In discussing the many Mars mission plans, Portree[4] notes that von Braun's thinking was influenced by the then-recent Antarctic Operation High Jump, a U.S. naval expedition in 1946-1947 consisting of 4000 men, 13 ships, and 23 aircraft. Von Braun explicitly stated that such a mission would tend to resemble Magellan's expedition around the world due to the need for self-reliance of the mission.

Von Braun's assertion in the late 1940's that any realistic mission to Mars with humans aboard would tend to resemble Magellan's expedition and have the same cost as a "small war" rapidly evolved with a variety of NASA studies (Early Manned Planetary-Interplanetary Roundtrip Expeditions or EMPIRE[17, 18]) and, after President Kennedy's 1961 speech, with considerations of architecture elements for reaching the Moon by the end of the 1960's. The focus was on Mars, but many of the EMPIRE concepts included a manned Venus flyby on the return leg to minimize propellant requirements. Flyby-only missions were also advocated to drop probes, based upon the (then) notion that robotic probes were too unreliable to drop probes successfully to Mars surface (a notion borne out by the track record of robotic probes up to that time).

Magellan's Voyage.[19, 20] It is worth recalling that while this first circumnavigation of the world is ushered in as one of the defining moments of exploration, it was entirely motivated by combined geopolitical and economic goals of determining the location of the Space Islands and breaking the Portuguese monopoly solidified only some ten years earlier. The expedition began 10 August 1519 as five ships left Seville for San Lucar de Barrameda; five 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	Reaches Spain 6 September 1522
Santiago	75	32	Wrecked on Argentine coast, winter during southern winter
TOTALS	480	234	

There were 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 command of Juan Sebastian de Elcano; 20 of the crew died of starvation before reaching the Cape Verde Islands; another 13 crew were abandoned there on 9 July (Cape Verde was a Portuguese holding). Eighteen men returned on the Victoria to Seville in 1522; four 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 one day early despite maintaining a careful log; they had gained a day by traveling west. In spite of the loss of four of five ships, the return of 26 tons of cloves along with nutmeg, mace, cinnamon, and sandalwood covered the expedition cost.

The cargoes were of sufficient value per weight that voyages continued involving Portuguese, Dutch, British, and American traders. 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.

"Small Wars". With respect to the other initial assertion of the cost being comparable to that of a "small war", comparison of financial costs of U.S. major wars allows such an assertion to be put into perspective[21].

TABLE 2: U.S. War Costs in Fixed 1990 Doillars.

Conflict	Cost in 1990 B$	Cost per capita (1990$)
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	2091.3	$15,665.17
Korea	263.9	$1,739.62
Vietnam	346.7	$1,692.04
Gulf War	61.1	$235.00

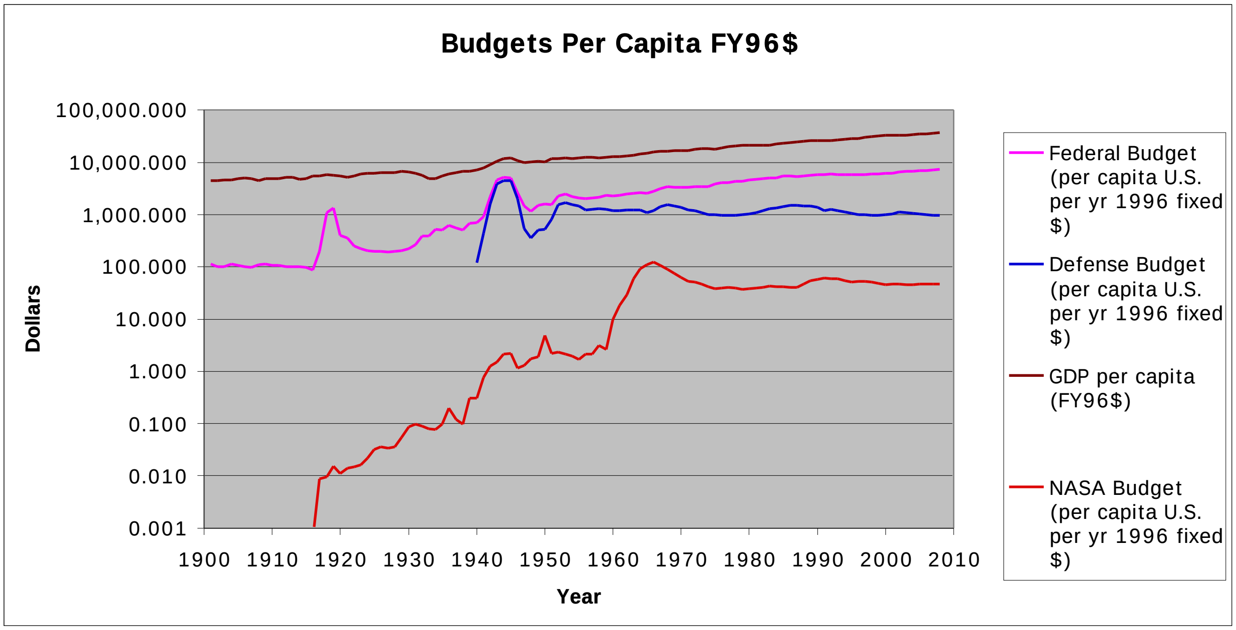

FIG. 4: Comparison of fixed year (1996) GDP, U.S. budget, U. S. Defense budget (1940 on), and combined National Advisory Committee on Aeronautics (NACA) and NASA budgets on a per capita basis. The NACA budget is for the years 1915-1959 when NASA was formed. All budgets are based upon actuals from 1901 or later until 2002 and projections from 2003-2008.

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. These events can be seen more clearly in Figure 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 (LOR) approach for getting men to the surface of 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 upon 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 the atmospheric pressure, all notion of aerodynamic landings such as used in the Von Braun scheme vanished. All notions of the possible presence of advanced life on Mars vanished as well[4].

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

Within two years, the Mars Voyager missions were cancelled and were 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 the Space Shuttle development was begun as a new initiative.

Over the next 30 years, plans for manned Mars missions have 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 of 1997[4]. Almost all conceivable architectures were advocated in these and other studies. In these studies, required masses in low-Earth orbit (sometimes referred to as "initial mass in low-Earth orbit," or IMLEO) are hundreds of tons and the estimated costs are from tens to hundreds of billions of dollars[4].

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

While there have been some reports on what a manned mission to destinations further 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 up into coherent, synergistic robotic and human components.

An Antarctic Paradigm?[27,28]

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 only discovered 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.

Highjump. While there had been growing commercial whaling and fishing competition off the shores of the continent, the modern history of Antarctica began for political reasons following the end of World War II. The U.S. commenced operations of Task Force 68 in 1946-1947. The context was disputed claims of Argentines and British during World War II and growing interests in the possible exploitation of natural resources following the war by a variety of governments.

With now Admiral Byrd in command, Operation Highjump established the Little America IV base and involved 13 ships, 33 aircraft and 4700 men. Larger than all previous expeditions put together, the operations surveyed ~350,000 square miles of the continent and photographed ~60 per cent of the coast.

Deep Freeze. High Jump was followed by Operation Deep Freeze I in 1955 that laid much of the groundwork for U.S. participation in the International Geophysical Year (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, this action took some 137 years from the first discovery.

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

To support Antarctic operations, both people and cargo must be moved in ant out.

In the 1990/1991 Deep Freeze operation, ~7200 metric tons 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 metric tons (slightly less 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 (ISRU) has not been a viable approach for providing needed resources for the bases, e.g. for fuel for the transport and electrical power. Even at these relatively large amounts of cargo that must be shipped in, the "breakeven" point for utilization of 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 what the scale is of large engineering projects. To give an idea of scale, Table 3 lists projects and items that have been built and Table 4 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 nine orders of magnitude for "extreme engineering."

TABLE 3. Extreme Engineering: What We Have Built

Item	Type	Mass (tons)
Great Wall of China[30]	Structure	730,000,000 (est)
Hoover Dam[31]	Structure	6,600,000
Golden Gate Bridge[32]	Bridge	811,500
Jahre Viking[33]	Ship (ULCC)	647,955
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 at launch[38]	Rocket	3,038.5
An-255 Cossack[39]	Cargo plane	600
Statue of Liberty[40]	Structure	225
Apollo 17[38]	Crewed space	30.34
Cassini[41]	Robotic space	5.655

Notes: Mass of the Great Wall is estimated from a density of 2.0 g cm^{-3}, length of 7300 km, average height of 10 meters, and average width of 5 meters; the Jahre Viking is an the largest Ultra-Large Crude Carrier (tanker) currently in maritime service; the Saturn V at launch is the mass as fully fueled prior to launch; Apollo 17 is the mass injected from Earth to the Moon; the Cassini mass is the total mass launched to Saturn prior to 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 space	2,301,000,000
L5 space habitat (10,000 pop.)[43]	Structure	10,618,000
Das Marsprojekt propellant[5]	Propellant	5,303,850
Das Marsprojekt vehicles[5]	Crewed space	37,200
ROOST post-Nova LV[44]	Launch vehicle	16,980
Saturn V-D concept[45]	Launch vehicle	9,882.1
Jupiter/Saturn fusion ship[26]	Crewed space	1,690
Completed ISS[46]	Structure	453.6
TAU-probe (interstellar)[47]	Robotic space	61.5
RISE probe (interstellar)[48]	Robotic space	1.1

Notes: The photon rocket was based upon a round trip at one "g" acceleration to Alpha Centauri using total matter annihilation for thrust; ROOST - Reusable One Stage Orbital Space Truck; the Saturn V-D was from a Marshall Space Flight Center study of 1968; the ISS is the International Space Station; TAU is the Thousand AU mission; RISE is the Realistic Interstellar Probe.

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…"

– R. Kipling[49]

The Previous NASA Strategic Plan[50]

The NASA Strategic Plan of 2003 posed three compelling questions that drive exploration: (1) How did we get here, (2) Where are we going, and (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 within the solar system on understanding the origin of the conditions for life on Earth, and possible origins of life elsewhere in the solar system. Focus has been on sites with water and suspected pre-biotic 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. In the case of robotic missions, "timely" can be from a year for reaching Mars orbit, to almost ten 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 design lifetime for spacecraft components and budgets for mission operations and for the science teams as they await the data.

"The Vision for Space Exploration"

On 14 January 2004, President Bush espoused a new vision for NASA[24]. There are 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 both to explore and to support decisions about the destinations for human exploration; and,

(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 serious, 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 the 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."

– R. A. Heinlein[51]

If the new initiative is to be sustained as the Antarctic program and not a short-term program like Apollo – and humans will be a major player in deep space – then one thing is clear: we will need to 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 – like Apollo – or built – like 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 metric tons in low-Earth orbit, an order for 1000 heavy lift launch vehicles (HLLVs) with a 20-MT to LEO capability will come in at a lower cost per unit than an order for 10.

If payloads to LEO will come in units of 1000 metric tons, then a new class oflaunch 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 1960's[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 to 5 million lbs to LEO (454 to 2270 Metric tons). Such EHLLVs would be very large and hence inherently expensive, so reusability would be required to be economic, an idea studied in, e.g. the "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 ~7200 metric tons 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 tons in LEO. Getting 7200 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 2000 MT to LEO EHLLV, the transport could be done with 150 flights, 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[53]

The same missions that were "difficult" in the NASA 1976 Outlook for Space Study[54] remain difficult today, primarily, but not exclusively, due to 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.

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 upon the body, potential destinations can be arranged into three groups as a function of their escape velocity, indicative of the amount of high-thrust propulsive capacity required (Table 5) [53].

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	0.635
3	Titan	2.64
4	Titania	0.773
	Triton	1.45
	Pluto	~1.2

NASA's Project Prometheus is a first step toward trying to solve these transportation difficulties. The first planned mission, the Jupiter Icy Moons Orbiter (JIMO)[55] will use a nuclear electric propulsion system powered by a fission reactor to address science goals in the Jovian system that cannot be addressed with a single mission otherwise. 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 will be cost: reactor + certification! + spacecraft + instruments/science.

The Role of Humans (Do We Need Astronauts?)

Robotic missions can be summarized as: 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 that, in turn, drives receiver and transmitter sizes and transmitter power. Thus data return drives power and, hence, mass, that, in turn, drives propulsion. Even with all the data returned, there is always still the lingering doubt of 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 grams of lunar material returned by the robotic Luna 24 probe. However, if one also takes into account 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, 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) require either double the time or quadrupling the propulsive requirements of a simple, fast flyby mission. If we take ~50 AU as the characteristic outer size of the solar system (the heliocentric distance to Pluto from the Sun near its aphelion in ~2113 as well as the distance to the most distant Kuiper Belt Objects seen to date), then the required mission time sets the required propulsive capability.

With a human crew, a maximum mission duration of four years (longer than Magellan's voyage!) would still be long, and perhaps unacceptable from both psychological as well as radiation exposure aspects. In addition, in the absence of a true 100% enclosed ecosystem, the mass of food, oxygen, and water for the crew increase with the mission time. To traverse the solar system in four years (roundtrip), a two-year voyage to Pluto would require accelerating to ~25 AU/yr and then decelerating by the same amount. The return voyage would require the same performance, for a total onboard capability of 100 AU/yr or ~500 km/s of delta V.

The corresponding specific impulse is ~51,000 s. This is significantly in excess of even nuclear thermal rocket capabilities, and, in the absence of practical controlled fusion, means that such a voyage could only be contemplated with a nuclear electric propulsion (NEP) system of a very advanced design.

This approach can provide for a quick estimate of what the implied systems must provide. Shorter distances or longer times yield less needed capability. A sample return mission to Pluto near aphelion that took 40 years to bring a sample back would require a delta V capability of 4 x (50 AU/20 years) = 10 AU/yr ~50 km/s. Similarly, a crewed mission to the Jupiter system at 5 AU with a roundtrip time of 4 years would also require a delta V capability of 4 x (5 AU/2 years) = 10 AU/yr ~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. Even comparing with a sample return mission with the same time scale for mission completion, mass, and its associated cost, remains the principal driver. For example, the Soviet lunar sample return mission Luna 16, 20, and 24, had masses of 5600, 5600, and 4800 kg, respectively. In contract, the Apollo spacecraft at translunar 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 Design Reference Mission (DRM, manned Mars) of 1997 that required an initial 303 tons[4]. This was a scrubbed version of the DRM of 1993 that took 6 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 low-Earth orbit 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.

Suppose the total ΔV capability is 50 km/s with a total "burn time" of 4 x 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 ~5600s). For a 3000 kg spacecraft, the initial propellant load would by 1800 kg. If this amount were to be processed over 600 days, the required mass flow rate is 3 kg/day or ~35 milligrams per second. The implied exhaust power is 51.7 kW, and acceleration is in the 10s to 100s of micro-gs. For a prime power conversion efficiency of 20% using an NEP system, the reactor thermal power would need to be ~260 kWth. These parameters are close to current specifications for the reactor concepts being studied for the Jupiter Icy Moons Orbiter (JIMO) spacecraft under Project Prometheus.

For a crewed expedition of ~300 metric tons, and the same scalings, the power consumption required would be up by the increased mass flow rate, a factor of 100 to ~5.2 MWe (megawatts electric), with a thermal reactor power output of ~26 MWth, 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 $\sim\tau/v_{exhaust}^2$, in this case ~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 ΔV of 500 km/s, the exhaust speed would need to increase by a factor of ~10 for efficient propellant usage. 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.

Human missions to the Jovian system may not be totally crazy, but certainly not easy, and 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."

– R. Kipling[49]

"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."

– W. von Braun[59]

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 robotically reach Pluto, and a stalled human program. Future plans now being acted upon show promise for enhancing robotic missions with nuclear electric propulsion 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 hundred 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 decide whether we will be there as well. It really is up to us.

TABLE 6. A Future Exploration Plan – Selected Milestones

Year	Goal
2013	Mars Sample Return
2015	Interstellar Precursor Mission launched ("Interstellar Probe")
2015	Launch autonomous robotic tour of Jupiter system (JIMO)
2020	Human launch to L2 for servicing of James Webb Space Telescope
2023	JIMO arrives at Jupiter
2025	Crewed expedition to a Near Earth Object – demonstrate hazard mitigation
2025	Launch robotic tour to Neptune system
2030	Permanently staffed lunar base
2030	Human mission to Mars
2035	Commence 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 established
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." – W. B. Yeats[60]

Although crewed missions beyond the main asteroid belt may remain problematic (if even desirable) throughout this century, there are still major scientific questions that can be answered only 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. All of the 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 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.

Top-level elements and requirements include communications infrastructure, modular hardware that is evolvable and scalable (not-unlike Airbus or Boeing airliners), role and characteristics of a crew exploration vehicle (CEV) for multiple uses, minimum buys of large numbers of EELVs to keep unit costs – and the cost of access to space – down, need for cargo-capable HLLVs (or larger EHLLVs) to push past Apollo tasks on the Moon, and prepare the way for Mars, roles for L2 as a way-station and observatory for other star systems, and roles for automated CEVs wed to Prometheus vehicles for outer solar system exploration and sample returns. The current goal is to answer fundamental questions of 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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