THE ROAD TO RED ROCKS: A HISTORY AND CRITIQUE OF MARS EXPLORATION AND SELECT MARS MISSION MODELS

A Master Thesis

Submitted to the Faculty

of

American Public University

by

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In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

May 2017

American Public University

Charles Town, WV

DEDICATION

To Camden, Christian, Emilee, Mom, and Papi. Your love, support, and patience made this possible. I am eternally in your debt.

ABSTRACT OF THE THESIS

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American Public University System, April 30, 2017

Charles Town, West Virginia

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Mars has been a stated goal of major space programs since the 1960's. However, humanity is always "a decade or so away." Beyond the technical issues associated with human spaceflight, the problem of launching a full-scale exploration of Mars is compounded by lack of proper funding, lack of political will, and an abundance of risk aversion. Using telerobotic exploration, both orbital and in situ observations of the Red Planet have revealed that it may once have been a hospitable home to life, but more detailed human exploration is needed to determine if life has ever existed there. Proposed mission plans for a crewed Mars mission were evaluated using a pass/fail grade based on crewmember health, funding feasibility, and sustainability. Such grading was accomplished using original materials about each plan to determine the feasibility of each area independent of the other two. Analysis reveals that while Robert Zubrin's *Mars Direct* plan has the greatest potential for a Mars mission in the shortest timeframe, SpaceX's Mars Colony Transport plan has the highest probability of achieving a crewed mission to Mars. I recommend a hybrid mission which uses the Mars Base Camp plan as a precursor and Zubrin's architecture as a springboard into the larger SpaceX colonization plan. This would be sufficient to drive both alacrity and mass colonization within 50 years.

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Introduction

Mars has held humanity's fascination for thousands of years. As the Apollo astronauts made their first steps onto the lunar regolith in 1969, laypersons and scientists around the United States, and the world, felt that humans were close to realizing their potential as a multi-planet species and were excited at the prospects the future held in space, particularly in respect to Mars. It seemed at that time that humanity was only a few short decades from becoming master of the solar system. As time passed, the reality of the situation was revealed. Space travel was and is expensive, adding a human being to a spaceship proved to increase that cost substantially. Before investing billions of dollars of funds into a mission which could fail at any number of critical points, governments requested that studies be conducted using probes, robotics, and orbiters. The robotic exploration of Mars has continued since the 1960's at roughly the same pace. The United States, Russia, the European Space Agency (ESA), and India have each placed an orbiter around the Red Planet. The US and Russia have each placed probes on the surface of the planet. Knowledge of Martian weather, topography, geology, climatology, mineralogy, and many other areas has advanced substantially. However, nearly 50 years after humans set foot on the Moon, humanity seems no closer to putting human beings on Mars.

Mars has the potential to be an important waypoint on humanity's march into the universe. It will be a proving ground for emerging technologies and a breeding ground for new and emerging technologies. It will be humanity's first interplanetary colonization effort and it has the possibility to become a trading outpost of remarkable political and industrial power. Moreover, Mars will be humanity's first steps toward becoming a Type 2 Civilization per

Zubrin's Taxonomy of Civilization Types.[1] Finally, colonizing Mars will also ensure humankind's survivability in the case of inhabitability of the Earth via natural or human causes.

Humanity has all the technology needed to conduct a humans-to-Mars mission. While some scientists and pundits claim that humanity must wait until new propulsion technologies bring the length of a Mars journey down, there is no need to wait until those technologies are mature. New launch technologies and emerging aerocapture and propulsive landing technologies are bringing the cost of launch down and the probability of a safe landing upon reaching Mars up. What is now lacking is the financial and political will to push the boundaries of the human experience and answer some of the most important questions humanity has posed. Using in situ resource management, new lean launchers, and atomic energy, it is possible to send humans to Mars as of the next practicable launch window in 2020. Only the will to go "all in" and commit to such an endeavor is lacking.

There have been many models of Martian exploration conceived of since rockets first began to pierce the sky. The very first scientific look at sending a human to Mars was conducted by Dr. Wernher von Braun, father of the US rocket program. From there many other have thought of new or different way to send human beings to Mars. Others yet have argued against such an endeavor in favor of spending the funds which might be used back on Earth. While it might be an easier experience to turn inward and not travel to other planets, it is simply against human nature not to do so. Of the various Mars exploration models, the most debated and talked about models at present (2017) are: Dr. Robert Zubrin's *Mars Direct*, Dr. Edwin "Buzz" Aldrin's *Mission to Mars*, NASA's Journey to Mars, Mars One, Lockheed Martin's Mars Base Camp, Andy Weir's *The Martian*, and Elon Musk's *Mars Colonization Transport*. Each of these models

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[1] Robert Zubrin, *Entering Space: Creating a Spacefaring* Civilization (Ney York: Jeremy P. Tarcher/Putnam, 1999), Ch.1.

has its merits and pitfalls. Each are more or less feasible using current or emerging technologies and funding models. Each manages the health of crewmembers differently, or not at all. All would be challenging if executed. However, it is the inclination of this author to compare and contrast these models and grade them on the areas of crewmember health, financial feasibility, and sustainability to determine which should be given the most attention and funding to become humanity's model for becoming an interplanetary species.

Historical Review: An Overview of Mars Exploration Efforts

Mars has fascinated the human species for millennia. The earliest known records of Mars as a heavenly body appear in the Senenmut star map, dated to 1534 BCE.[2] The Chinese, before the Han dynasty (206 BCE–220 CE), had observed the motions of planets and stars, including Mars. They had noted the occultation of Mars by Venus on several occasions in their writings.[3] The Greeks took much of their astronomical knowledge from Mesopotamian culture, which had associated Mars with the god Nergal (god of war), thus they named what is now called Mars, Ares after their god of war.[4]

What is typically called the Aristotelian/Ptolemaic model (geocentric) was originally written by Plato in *The Republic* (X.661E-617B). Aristotle used his own observation of an occultation of Mars by the moon in 365 BCE to codify what could be considered an early parallax method of determining objects relative distance from the Earth. Ptolemy, a Roman Egyptian, in the second century BCE further cemented the geocentric universe in Western

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[2] Bojan Novaković, "Senenmut: an ancient Egyptian astronomer," *Publications of the Astronomical Observatory of Belgrade* 85: 19–23, October 2008.

[3] Liu Ciyuan, "Ancient Chinese Observations of Planetary Positions and a Table of Planetary Occultations". *Earth, Moon and Planets* 40 (2): 111–117, February 1988.

[4] Franz Valery and Marie Cumont, *Astrology and religion among the Greeks and Romans*. *American lectures on the history of religions* (New York: G. P. Putnam, 1912), 46.

academia when he published *Almagest*, where he introduced the idea of perfectly circular epicycles for planetary orbit.[5]

In 1543, Nicolas Copernicus revolutionized the scientific model of the universe by publishing his heliocentric model in *De revolutionibus orbium coelestium*. In 1621, Johannes Kepler published his *Epitome of Copernican Astronomy* (translation). In this work, with the help of detailed observations by Tycho Brahe, Kepler laid down his Laws of Planetary Motion, wherein he made the astute assumption that planets do not move in perfect circles, as proposed by Copernicus, but in ellipses with the Sun at one foci.[6]

In 1877, Giovanni Schiaparelli produced the first detailed map of Mars using a 22-cm telescope. On his map, he had labeled some features *canali*, which was wrongly translated into English as "channels." The term was originally meant to convey that the features naturally occurred on the planet's surface. Schiaparelli published his book, *La vita sul pianeta Marte (Life on Mars)* in 1893. This work of literature influenced American astronomer Percival Lowell to write several published works concerning life on Mars. As telescopes continued to advance in resolution and clarity during the 20th Century, the "channels" theory began to fail. Finally, during the Mariner program, the "channels" died a quiet death as higher resolution photography from close proximity showed that there were no such features.[7] Until the middle of the 20th century, thoughts of interplanetary travel and even space travel were the realm of fantasy writers such as H. G. Wells and Gustavus Pope. It was only after the development of novel technologies in the Second World War that spaceflight was even considered a distinct possibility.

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[5] Christopher M. Linton, *From Eudoxus to Einstein: a history of mathematical astronomy* (Cambridge: Cambridge University Press, 2004), 62.
[6] Ibid.
[7] George Basalla, "Percival Lowell: Champion of Canals". *Civilized life in the Universe: scientists on intelligent extraterrestrials* (New York: Oxford University Press US, 2004), 67–88.

To Mars by Proxy

The National Aeronautics and Space Administration (NASA) was formed in 1958 by the Eisenhower administration. This was in response to the first orbiting of a satellite, *Sputnik*, by the Soviet Union in 1957. NASA was preceded by the National Advisory Committee for Aeronautics (NACA), and absorbed that entity when established. The basis for NASA's operations was written into law with the National Aeronautics and Space Act of 1958. Primary amongst that civilian organization's duties was the "expansion of human knowledge of phenomena in the atmosphere and space."[8] As part of their development of a planetary sciences program, NASA focused almost entirely on the Moon during the program's infancy. However, as early as 1958, the Jet Propulsion Laboratory (JPL) was exploring the technical feasibility and scientific merit of extensive planetary research for Mars and Venus using probes.[9] In an extremely astute and forward thinking report, JPL chief of research and analysis, Albert Hibbs even explored the need for planetary protections in the search for extraterrestrial life.[10] This report to NASA, among others, shows that the administration felt that a multi-pronged approach with autonomous probes and landers and crewed spaceflight would be the best way forward.

This multi-pronged approach led to the Mariner flybys of the 1960's and 1970's. The first probe to successfully fly by Mars and send back data and pictures was *Mariner 4* on July 14 and 15, 1965. *Mariner 4* captured 21 images of the Martian surface in a discontinuous swath which covered approximately 1 percent of the Martian surface from 10,000 km. The images totaled approximately 5.2 million bits of data (about 650 kilobytes). Because of data transmission rates

[8] National Aeronautics and Space Act of 1958, Public Law 85-568, *US Statues at Large* 72 (1958): 427, §102. c.1.
[9] John M. Logsdon, ed., *Exploring the Unknown*, vol. 5, *Exploring the Cosmos* (Washington, D.C.: NASA, 1995), 314.
[10] Albert Hibbs, ed., "Exploration of the moon, the planets, and interplanetary space," in John M. Logsdon, ed., *Exploring the Unknown*, vol. 5, *Exploring the Cosmos* (Washington, D.C.: NASA, 1995), 316.

over interplanetary distances (8.3 bps/ 33.3bps for *Mariner 4*), the data transmission phase took at least 43 hours to complete after a post-flyby Mars occultation of the craft. The images gathered showed a cratered Martian surface similar to that of the moon.[11]

This was followed by the successful dual Mars flyby of the *Mariner 6* and *Mariner 7* craft in 1969. Where *Mariner 4* was primarily focused on acquiring images of the surface of Mars, *Mariner 6* and *7* also included instrumentation to detect UV and IR emissions and radio refractivity of the atmosphere. Though launched thirty-one days apart (24 February 1969 for *Mariner 6* and 27 March 1969 for *Mariner 7*) the craft conducted their respective fly-bys only five days apart (31 July and 5 August, respectively). *Mariner 6* returned 49 far encounter and 26 near encounter images of Mars, and Mariner 7 returned 93 far and 33 near encounter images.[12] *Mariner 7* was reprogrammed after the *Mariner 6* fly-by to focus on areas of interest to NASA scientists, thus it returned more images. Both craft flew by at approximately 3430 km and the returned data mapped 20% of the surface area of the planet. These missions were also the first to study the atmosphere of Mars and characterized the southern polar ice cap as being composed of carbon dioxide.[13]

For the Soviet Union, the 1960s was a period of failure in their Mars exploration pursuits. Where the United States attempted to launch four Mars missions and had three successes, the Soviet Union attempted eight missions to Mars, none of which were successful. *Marsnik 1* and *2* (1960) both failed to reach earth orbit. *Korabl 11* (1962) failed to reach earth orbit. *Korabl 13* (1962) reached earth orbit, but broke up during trans-mars injection (TMI). *Mars 1* (1962)

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[11] "Mariner 4," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1964-077A.
[12] "Mariner 6," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1969-014A.
[13] Ibid.

successfully made the TMI burn, but contact was lost after a course correction burn en route to Mars. *Zond 2* repeated this failure in 1964. *Mars 1969a* and *1969b* (planned Martian orbiters) both failed to enter earth orbit.[14] As for US failures during the 1960's, *Mariner 3* was successfully launched in late 1964, but an instrument protection fairing failed to release and the craft was unable to attain the correct trajectory for the Martian fly-by.[15]

The 1970's led to success in the field of Martian probes for both the United States and for the Soviet Union. The first spacecraft to orbit another planet came in 1971 with *Mariner 9* entering Martian orbit on 14 November 1971. This only barely beat out the Soviet Union, as *Mars 2* and *3* both orbited the planet within a month of *Mariner 9*. The three spacecraft reached the planet at the worst possible time. A dust storm had begun to form in September, and by the time of the arrival of the spacecraft had enveloped the entire surface of the planet. Both *Mars 2* and *3* had planned lander/rovers as part of their mission profile. Each released its lander about four-and-a-half hours prior to entering Martian orbit. *Mars 2*'s descent module entered the atmosphere at a steeper angle than was planned and the entire landing system malfunctioned resulting in the crash of the lander at 45°S, 313°W. Though it landed in a failure mode, the *Mars 2* lander became the first human-made object to land on Mars, carrying the Soviet coat of arms along with it. The Mars 3 lander fared better, achieving a soft-landing at 45° S, 158° W using aerobraking, parachutes, and retro-rockets. However, as it landed during the worst dust storm in recorded history, it was only operational for 20 seconds. It may have been able to activate its tiny rover in that time[16], but the accuracy of that claim would be in doubt as no data from the rover

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[14] "Missions to Mars," The Planetary Society, last modified 2017, accessed April 29, 2017, http://www.planetary.org/explore/space-topics/space-missions/missions-to-mars.html.
[15] "Mariner 3," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1964-073A.
[16] "Missions to Mars."

was received. *Mars 2* was successfully inserted into an 18-hour orbit with an inclination of 48.9°.[17] *Mars 3* had experienced fuel losses en route. As a result, the orbiter could not be put in a planned 15-hour orbit and only had enough fuel to place it in a 12-day, 19-hour orbit with a similar inclination to that of *Mars 2*.[18] In total, *Mars 2* and *3* returned 60 images and used occultation radiography to characterize the Martian atmosphere.[19]

Mariner 9 was placed in an approximate 12-hour orbit about the planet, where it gathered data and mapped the planet from 14 November 1971 to 27 October 1972. It returned 54 billion bits of data, including 7,329 images which covered the entire surface of the planet and its satellites, Phobos and Deimos. The data also provided information on dust storms and aeolian activity.

It is important to place these events in the context of the Cold War and the Space Race. The United States and the Soviet Union were, during this time, in a sometimes-military conflict to gain global dominance in the aftermath of World War II. One of the most public aspects of this conflict for control was the Space Race. For every achievement by one side in that race, the other would attempt to outdo the other. The Soviet Union began the Race in 1957 with the launch of *Sputnik* and culminated in the July 1969 moon landing of *Apollo 11* by the United States. One of the positive side effects of the Cold War was the progression of science in many fields. Astronomy, nuclear physics, planetary imaging, meteorology, rocketry and other fields received a boost by the ongoing conflict between the world superpowers. It is evident by this that the desire to be viewed as a leader in the field led to some missions being attempted using sub-

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[17] "Mars 2," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1971-045A.
[18] "Mars 3," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1971-049A.
[19] Ibid.

par technology or missions being rushed to try to "beat" the other side to whatever achievement was being pursued. Ofttimes, rushed missions led to loss of mission (LOM).

This was the case for *Mars 4*, *5*, *6*, and *7*. The Soviet Union had advanced knowledge of America's attempt at a soft landing on the Martian surface during the 1975 synodal opportunity. In response, they planned a series of missions during the 1973-74 launch window. However, each of these missions was rushed and was launched with flawed electronics that led to various failures throughout the mission series. *Mars 4* was planned to orbit the planet on 10 February 1974, but due to the electronics failure, the retro-rockets meant to inject the spacecraft failed to fire. Mission planners thus turned *Mars 4* into a fly-by.[20] *Mars 5* successfully orbited the planet on 12 February 1974 in a 24-hour, 53-minute orbit. However, the spacecraft failed due to a loss of pressurization in the instrumentation module after 22 orbits and the mission was ended.[21] Mars 6 was a fly-by/lander combination. The lander was released 48,000 km from the planet. The main bus passed within 1,600 km of Mars. The lander transmitted 226 seconds of data during descent, though it was mostly unreadable due to the aforementioned electronics issues. Contact with the lander ceased in "direct proximity to the surface,"[22] either due to vibration from retro-rocket firing or due to contact with the surface.[23] Mars 7 encountered the same electronics issues, which caused the lander to be released four hours prematurely. This caused the lander to miss the planet by 1,300 km.[24] The combined effort of these four missions did give scientific

[20] "Mars 4," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1973-047A.
[21] "Mars 5," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1973-049A.
[22] "Mars 6," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1973-052A.
[23] Ibid.
[24] "Mars 7," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1973-053A.

knowledge of Mars. Radio occultation experiments proved the existence of the Martian ionosphere and measured the surface atmospheric pressure at 6.7 millibars.[25]

As for the United States, the entirety of their Mars probe program in the 1970's was summed up in two linked missions, *Viking 1* and *2*. The *Viking* program grew out of the *Mars Voyager* program (not to be confused with the "Grand Tour" *Voyager* missions which launched in 1977 and continue their extended missions as of this writing). The *Mars Voyager* program was first envisioned in 1960 as an advanced concept mission which would follow the *Mariner* missions. The *Mars Voyager* mission would take new data gleaned from the *Mariner* missions and use it to define new scientific questions raised by their previous interplanetary efforts. *Mars Voyager* would take advantage of larger launchers developed during the *Mariner* program to send orbiter/lander pairs to Mars. However, the *Mars Voyager* program had to compete for funding against an array of programs for NASA and the federal government. The Apollo project was so expensive that it eclipsed other programs in spending, requiring reallocation of funds from most of the other programs which NASA had originally planned. Apollo being the priority in the Space Race meant that money would not be available for other projects until the lunar goal was met. As the United States government was also involved in a costly war in Southeast Asia, NASA budgets were already under fire in Congress's quest to cut spending. As such, the *Mars Voyager* program was funded well into the developmental stage to the point of that a request for proposal was published, but it was finally cut in 1967.[26] As with any large federal expenditure, politics and funding are the two largest hurtles which must be overcome. No matter how excellent a mission is proposed and no matter how prescient the science being conducted, if

[25] "Missions to Mars."
[26] Edward C. Ezell and Linda N. Ezell, "Voyager: Perils of advanced planning, 1960-1967," in *On Mars: Exploration of the Red Planet, 1958-1978* (Washington D.C.: NASA History Office, 1984), accessed April 29, 2017, https://history.nasa.gov/SP-4212/ch4.html.

those with the power of the purse withhold their graces, it will not get off the ground. However, the planning for *Voyager Mars* did have the effect of enlightening the community at NASA in efficient planning of missions. It also laid much of the conceptual groundwork for the *Viking* missions to come.[27]

As for the *Viking* missions, each was designed and implemented as an orbiter/lander pair with advanced scientific experiments on board. The purpose of the orbiters was strictly to characterize the Martian surface and relay enough data to certify landing areas for each of the landers. Each orbiter was also to act as a communication relay for the landers, sending in situ data back to Earth.[28] The most pressing scientific question posed in *Viking* planning was that of the presence of life on the Martian surface. To attempt to answer this question, each lander was equipped with four biology experiments that, it was hoped, would either prove or disprove the existence of life on Mars, either past or present. These experiments were: the gas chromatograph-mass spectrometer (GCMS), gas exchange experiment (GEX), labelled release (LR) experiment, and the pyrolytic release (PR) experiment.[29]

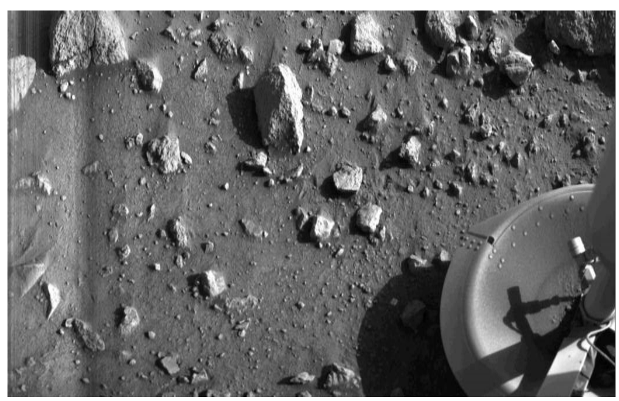

Figure 1: The first clear picture returned from the Martian surface. Viking 1 Lander, 20 July 1976. Source: NASA, https://www.nasa.gov/multimedia/imagegallery/image_feature_910.html.

Viking 1 was launched on 20 August 1975 and *Viking 2* was launched on 9 September 1975. They were both launched aboard Titan IIIE/Centaur rockets and had an identical launch mass of 3,527 kg. *Viking 1* entered Martian orbit on 19 June

[27] Ibid.
[28] "Viking 1 Orbiter," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1975-075A.
[29] Ezell and Ezell, "Science on Mars," in *On Mars: Exploration of the Red Planet, 1958-1978* (Washington D.C.: NASA History Office, 1984), accessed April 29, 2017, https://history.nasa.gov/SP-4212/ch11-5.html.

1976 and *Viking 2* followed suit on 7 August. Each orbiter began imaging the planet approximately five days before entering orbit and spent approximately 30 days in orbit certifying landing sites and mapping the planet before releasing its lander. *Viking 1* released its lander on 20 July and it landed successfully at Chryse Planitia after approximately three hours.[30] *Viking 2* released its lander on 3 September and it landed successfully at Utopia Planitia.[31]

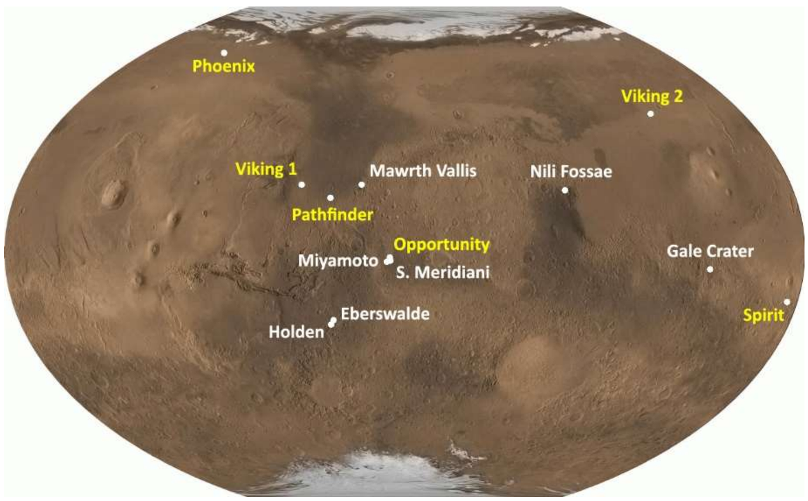

Figure 2: Disc projection of Mars showing landing sites of successful American landers up to 2008. Also noted are seven possible landing sites for Mars Science Laboratory Curiosity Rover. Source: NASA, Jet Propulsion Laboratory, 18 August 2008, https://mars.nasa.gov/msl/news/whatsnew/index.cfm?FuseAction=ShowNews&NewsID=74.

The *Viking* science studies returned interesting results which have been debated in the years since. The GCMS experiment humidified regolith samples for six sols (Martian days) then the regolith was wet with a nutrient solution and the gas above the regolith was analyzed using the gas spectrometer. In theory, the experiment would be able to detect biologics on the order of

[30] "Viking 1 Orbiter."
[31] "Viking 2 Orbiter," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1975-083A.

parts per billion. GCMS returned a negative result for organics present in Martin soil, a surprising result as the planet has been bombarded by comets, asteroids, and space dust for millions of years, and these objects seem to contain organic compounds in general.[32]

The LR experiment was conducted by wetting regolith with ^{14}C (radioactive carbon)-labeled organic compounds and the gaseous release was monitored for evolution of the radioactive carbon at different temperatures. Initially, the experiment returned a positive result for biologics, but subsequent control runs of the experiment returned negative results. Subsequent in situ investigations conducted on the *Phoenix* lander found evidence of perchlorates on the Martian surface which could explain the control tests from the Viking landers.[33] However, as of the time of this writing there is still debate about whether the tests were inconclusive or negative for life on Mars.[34]

As can be seen by the previously mentioned interplanetary missions, the height of the Space Race produced a need for new science. No matter that the Soviet Union had so many failures and the United states had many successes. Both sides of the Space Race had an inherent need to outdo the other at any cost. Science was the true winner of the Space Race. It was a time of learning how to do the "impossible." When, during the 1970's a period of detent was evident, both sides of the Cold War began programs that were less expensive and more cooperative with

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[32] Bill Steigerwald, "NASA Goddard Instrument Makes First Detection of Organic Matter on Mars," NASA, December 16, 2014, accessed April 29, 2017, https://www.nasa.gov/content/goddard/mars-organic-matter.

[33] Perchlorate is known to break down organic compounds when heated to >350°C. As the *Viking* control samples were heated to 600°C, there is strong evidence to suggest that organic compounds *could have* been present in quantities of up to 0.01% and still have given the same results (see Biemann, K., and J. L. Bada (2011), Comment on "Reanalysis of the Viking results suggests perchlorate and organics at midlatitudes on Mars" by Rafael Navarro-González et al., J. Geophys. Res., 116, E12001, doi:10.1029/2011JE003869.) The finding of no organic compounds on Mars would seem to be impossible with the planet receiving constant bombardment from asteroids, meteorites, and comets for millions of years. Therefore, the *Viking* tests should be considered inconclusive, and further study should be conducted.

[34] Richard C. Quinn, et al., "Perchlorate Radiolysis on Mars and the Origin of Martian Soil Reactivity," *Astrobiology* 13, 6 (June 2013): 515-520, accessed April 29, 2017, http://dx.doi.org/10.1089/ast.2013.0999.

one another. For interplanetary science, this was a disaster. After *Viking*, Mars became secondary or tertiary to the Soviet *Salyut* space station program and the United States' upcoming Space Transportation System (Space Shuttle) program. Apart from two failed Soviet missions in the late 1980's (*Phobos 1* and *2*), no missions were aimed at Mars until nearly 20 years after the *Viking* landings. This could be evidence that human endeavor is centered around conflict, i.e. the Cold War bred the Space Race, which injected massive sums of money into the aerospace industry and drove discoveries for the national glory for exploration and being the first to accomplish large goals. Robert Zubrin, founder of the Mars Society, contends that in the absence of conflict the Space Race would never have happened and humanity would only recently have landed on the moon, let alone have learned so much about Mars via probes. However, the teeth, and thus the drive, of the Space Race were removed from space by the Outer Space Treaty of 1967.[35]

Martian Renaissance: 1996 - Present

The 1970's and 1980's were discouraging for Mars science. The Soviet Union traversed through an economic collapse that brought about the end of both the Soviet Union and the Cold War. Thus, their space program was primarily focused on near-earth human missions leading up to and in support of the *Mir* space station. NASA was entrenched in the Shuttle program and the costs associated with those missions. Therefore, Mars and interplanetary missions in general fell even further down the mission docket. The two probes that were launched were by the Soviet Union were *Phobos 1* and *2*, which intended to study the Martian moon Phobos. *Phobos 1* failed two months after its 1988 launch, when incorrect programming data was uploaded to the spacecraft. This data caused the orbiter to turn its solar panels away from the sun which caused

[35] Zubrin, *Entering Space*, 9-10, 14.

mission failure.[36] *Phobos 2* successfully entered Martian orbit in 1989, but when it began its approach to the moon Phobos, its main computer malfunctioned causing loss of the mission.[37]

The United States also experienced failure during the 1992-93 launch period when the *Mars Observer* spacecraft failed just three days before entering Martian orbit. The cause for the loss of this mission remains a mystery, but an investigation found that the most probable cause of loss was due to a fuel line rupture during tank pressurization which would have sent the craft spinning out of control.[38]

In 1996, a new renaissance for Mars missions started to form. This began with the launch of NASA's *Mars Global Surveyor* (MGS) on 7 November 1996. The MGS flew for 10 months before entering Mars orbit in September of 1997. A failure of one of the solar panels to properly latch, as well as subsequent structural damages, caused a delay in science operations, due to the inability to use the original aerobraking schedule to circularize the orbit of the craft. This delay lasted until 1999, when the craft successfully entered a 118-minute polar sun-synchronous orbit at 378 km. The original mission was designed to conduct one Martian year of scientific evaluation and mapping. The craft was extremely successful in its mission and was subsequently extended until contact with the craft was lost on 2 November 2006. MGS produced the highest-resolution images of the Martian surface yet achieved from orbit. It also studied surface composition, topography, gravity variances and fields, weather, and climate.[39] It is considered one of the most successful missions within the field of planetary sciences.[40]

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[36] "Phobos 1," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1988-058A.
[37] "Phobos 2," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1988-059A.
[38] "Mars Observer," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1992-063A.
[39] "Mars Global Surveyor," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1996-062A.
[40] "Missions to Mars."

The next Mars mission was launched by NASA just a month after the launch of MGS. *Mars Pathfinder* and its rover, *Sojourner*, launched on 4 December 1996 and arrived at Mars on 4 July 1997. *Pathfinder* used a novel air-bag landing system to bounce to a successful landing at 19.33°N, 33.55°W, the mouth of the Ares Vallis. Two days later, *Sojourner* ventured forth onto the Martian surface. The mission was scheduled to continue for 30 days, but was extended until loss of signal on 27 September 1997. The mission was the second of NASA's Discovery-class missions and was intended as a feasibility study to show that a low-cost mission could land on Mars.[41]

The Failures of the 1990's

During the 1998-99 period, NASA and the Japanese Institute of Space and Astronautical Science (ISAS) experienced several failures of their Martian attempts. NASA launched the *Mars Climate Orbiter* on 11 December 1998. The orbiter was lost during the orbital insertion phase of the mission on 23 September 1999, due to a mathematical conversion error in the program placing the orbiter too close to the Martian surface during insertion.[42]

ISAS launched the *Nozomi* orbiter on 3 July 1998. It was lost due to many errors in astrodynamics calculations, notably not gaining enough speed during an Earth flyby and using more fuel than calculated. ISAS attempted to wrangle the orbiter to Mars using two more Earth flybys, but a powerful solar flare in 2002 damaged the craft's main computer which caused its

[41] "Mars Pathfinder," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1996-068A. Discovery-class missions were conceptualized in 1992 as part of the "better, faster, cheaper" plan for NASA proposed by then Administrator Dan Goldin. Discovery-class missions are cost-capped at US$425 million, including post-launch operating cost.
[42] "Mars Climate Orbiter," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1998-073A

liquid hydrazine fuel to freeze during the final approach to Mars. ISAS was unable to orbit the planet and the craft was lost in a heliocentric orbit.[43]

NASA launched *Mars Polar Lander* on 3 January 1999. It was scheduled to land on Mars in December 1999, however the last contact with the lander occurred when the antenna was turned to prepare the craft for landing. It was determined that a faulty software system most likely caused the retro-rockets to shut down early causing the lander to crash. Lost with the lander were two penetrators and the first privately funded experiment to go to Mars, the Planetary Society's Mars Microphone.[44]

International Mars Collaboration

In the post-Cold War era, international collaboration has become the keyword for most space exploration efforts. The International Space Station was the largest of these projects, but interplanetary exploration also took on an international flair. The 2000's were a time when smaller agencies in space exploration took the forefront. The European Space Agency (ESA), the United Kingdom, China (CNSA), India (ISRO), and the Russian Federation (RKA and Roscosmos) all attempted Mars missions to various levels of success.

The first mission of the 2000's was NASA's *2001 Mars Odyssey*. It was launched on 7 April 2001 and successfully entered Martian orbit on 24 October 2001. *Odyssey* was originally designed to operate until July 2004. *Odyssey*'s primary mission was to conduct mineralogical study of the planet's surface and to measure the radiation environment. It was also to act as a

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[43] "Nozomi," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1998-041A.
[44] "Mars Polar Lander," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1999-001A and "Missions to Mars."

communications relay for future missions.[45] As of 2017, *Odyssey* remains operational, setting the record for longest-lived spacecraft in orbit around a planet other than Earth.[46]

In 2003, the ESA became the first international organization to attempt to reach Mars with *Mars Express* and *Beagle 2*, an orbiter/lander pair. They were launched on a Russian rocket on 2 June 2003 and reached Mars in December 2003. The UK designed *Beagle 2* lander was released from *Mars Express* before it entered orbit. *Mars Express* entered a highly elliptical orbit, which allowed for greater communication downlink time with Earth. The *Beagle 2* entered the Martian atmosphere on 25 December, however it never returned any data and was declared lost.[47] The *Beagle 2* lander was imaged from orbit by NASA's *Mars Reconnaissance Orbiter* in 2015.[48] Even with the failure of its lander, *Mars Express* was successful in achieving its main goals of mapping the surface, radar sounding of the subsurface to the permafrost level, atmospheric composition analyses, and analysis of the interaction between the Martian atmosphere and the interplanetary medium.[49] *Mars Express*'s mission was extended several times, with the latest extension running through the end of 2018.[50]

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[45] "2001 Mars Odyssey," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2001-014A.

[46] Guy Webster, "NASA Mars Odyssey orbiter resumes full operations," NASA/JPL, December 28, 2016, accessed April 29, 2017, https://mars.jpl.nasa.gov/news/2016/mars-odyssey-mission-status-report-orbiter-recovering-from-precautionary-pause-in-activity.

[47] "Mars Express," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2003-022A.

[48] Guy Webster, "'Lost' 2003 Mars Lander Found by Mars Reconnaissance Orbiter," NASA/JPL, January 16, 2015, accessed April 29, 2017, https://www.nasa.gov/jpl/lost-2003-mars-lander-found-by-mars-reconnaissance-orbiter/.

[49] "Mars Express: Objectives," ESA, last modified August 26, 2003, accessed April 29, 2017, http://sci.esa.int/mars-express/31023-objectives/.

[50] "Two-year extensions confirmed for ESA's science missions," ESA, November 22, 2016, accessed April 29, 2017, http://sci.esa.int/director-desk/58589-two-year-extensions-confirmed-for-esa-s-science-missions/.

Mars Exploration Rovers: Robots Lead the Way

During the summer of 2003, NASA launched a pair of landers to Mars, *Spirit* and *Opportunity*. The rovers were identical, and carried identical sets of scientific experiments. The experiments had several goals: search for evidence of the past existence of water; determine the composition of minerals, rocks, and soils in the landing area; determine what geologic processes formed the area; substantiate or disprove observations made from orbiting instruments; conduct detailed search for iron-bearing minerals; and use geological clues to assess the environment which may have been present if and when water existed in the region. Landing sites were chosen which had the appearance of having either been formed by water or having had extant water present at some point in the past. Each rover was designed for a 90-day mission lifetime. Each rover was designed with six wheels, the front and back pairs being independently steerable. In theory, each rover could possibly traverse 100 m per day at about 3.5 cm/sec. However, due to collision avoidance protocols, on a perfectly flat terrain each was limited to approximately 1 cm/sec.[51]

Figure 3: Artists' rendition of a Mars Science Lab rover on the Martian Surface. Source: NASA, https://mars.nasa.gov/programmissions/missions/present/2003/

The Mars Exploration Rover (MER) systems included several interesting aspects that show significant advancement from previous missions. Primary amongst these advancements is the ability to traverse autonomously. Until the MER project, rover movement on Mars was telerobotic, i.e. a human on Earth would give a command to the rover, which would execute the command. This was slow and laborious process, as communication times varied between 6 and 44 minutes round-trip. While MERs also used commands programmed by a human once per day,

[51] "Spirit," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2003-027A.

they also used an algorithm based autonomous system using the stereovision pan-camera. Using the Grid-based Estimation of Surface Traversability Applied to Local Terrain (GESTALT) algorithm, the rovers could move with minimal interaction with a human operator, which allowed for a much more robust mission.[52] Each MER also had the ability to use visual odometry to determine distance traveled. This advancement began on MER as an extra benefit, but quickly became mission critical. MER typically would use wheel odometry, a measure of how much distance is traveled by the wheel. However, this method could not account for wheel slippage and loss of traction on difficult terrains. Therefore, the visual odometry algorithm was developed to provide a secondary method of providing accurate rover positions. This allowed the rovers to provide their position with less than 2.5% position error and less than 5° rotation error over short distances (approximately 25-29 m). This method used terrain landmarks to identify position then made comparisons for each movement segment. There were difficulties when using this method on flat terrain with few landmarks, but these were overcome using the tracks left by the rover itself.[53]

MER *Spirit* was the first to launch, on 10 June 2003. It landed on Mars on 4 January 2004 using the airbag landing method proven by *Pathfinder*. Its landing site was at 14.572° S, 175.478° E, in the Gusev Crater. On 15 January 2004, scientific operations began when *Spirit* disembarked from its landing platform and began its exploration of the surface. *Spirit* conducted scientific evaluation and exploration over about 10 km of traverse until 23 April 2009, when it became stuck in a patch of soft regolith. Unable to reposition itself to properly orient its solar

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[52] Edward Tunstel, "Operational Performance Metrics for Mars Exploration Rovers," *Journal of Field Robotics* 24, no. 8/9 (August 2007): 651-670, accessed 29, 2017, Applied Science & Technology Source, EBSCOhost.
[53] Mark Maimone, Yang Cheng, and Larry Matthies, "Two Years of Visual Odometry on the Mars Exploration Rovers," *Journal of Field Robotics* 24, no. 3 (March 2007): 169-186, accessed April 29, 2017, http://dx.doi.org/10.1002/rob.20184.

panels to recharge its batteries, it was unable to survive the Martian winter. Contact with *Spirit* was lost on 22 March 2010.[54]

MER *Opportunity* launched on 8 July 2003, and reached Mars on 25 January 2004. It landed in a small crater at Terra Meridiani 1.946° S and 354.473° E. This location was chosen because an abundance of hematite, an iron-rich mineral typically formed in the presence of water, was detected from orbital installations. On 29 January, *Opportunity* separated from its landing platform and began its science mission.[55] As of April 2017, the *Opportunity* mission continues. The rover has traversed 44.41 km as of the mission update on 11 April 2017.[56]

One of the major goals of the MER program was to "prepare the way for human exploration of Mars."[57] The MERs have collected data on soil characteristics, seasonal temperature changes, solar radiation, and atmospheric dust. This data will be used by mission and equipment designers in the future for creating spacesuits and habitats for human use on Mars. These rovers have also proven that equipment can be designed and delivered to Mars that can last far beyond mission design times.[58]

The next mission, a NASA orbiter named the *Mars Reconnaissance Orbiter* (MRO) was launched on 12 August 2005. This orbiter had a mission of completing one Martian year of imaging and analyses of the Martian surface. It successfully entered Martian orbit on 10 March 2006. After orbital insertion, it began a six-month process of lowering its orbit from a 400 x 35000 km capture orbit to a 255 x 320 km science orbit. It is in a sun-synchronous orbit with a

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[54] "Spirit."
[55] "Opportunity," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2003-032A.
[56] "Opportunity updates," NASA/JPL, last modified April 25, 2017, accessed April 29, 2017, https://mars.nasa.gov/mer/mission/status_opportunityAll.html.
[57] "Goal 4: Prepare for human exploration," NASA/JPL, n.d., accessed April 29, 2017, https://mars.nasa.gov/mer/science/goal4-results.html.
[58] Ibid.

period of 112 minutes. MRO was used extensively in imaging landing sites for the *Phoenix* lander and the Mars Science Laboratory *Curiosity*. To accomplish its mission, MRO was sent with an array of different cameras, radiometers, sounders, and spectrometers. These were:

> "the High Resolution Imaging Science Experiment (HiRISE), a visible stereo imaging camera; the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), a visible/near-infrared spectrometer to study the surface composition; the Mars Climate Sounder (MCS), an infrared radiometer to study the atmosphere, a shallow subsurface sounding radar (SHARAD) provided by the Italian Space Agency to search for underground water; the Context Camera (CTX), to provide wide-area views; and the Mars Color Imager (MARCI), to monitor clouds and dust storms."[59]

Using these tools, MRO has made many discoveries and captured images of both *Phoenix* and *Curiosity* during the entry, landing, and descent (EDL) phases. For discoveries, it used the SHARAD sounder to determine the volume of water ice at the northern pole to be 821,000 cubic kilometers.[60] Using the CTX camera, and confirming the composition of the material with the CRISM tool, it imaged new impact craters on the surface, showing water ice beneath the crust.[61] HiRISE and CRISM were also used to confirm the existence of flowing perchlorate on the Martian surface.[62] MRO remains on

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[59] "Mars Reconnaissance Orbiter," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2005-029A.
[60] Keith Cowing, "Radar map of buried Mars layers matches climate cycles," September 22, 2009, archived, accessed April 29, 2017, https://web.archive.org/web/20101221190147/http://onorbit.com/node/1524.
[61] Colin M. Dundas, et al., "HiRISE observations of new impact craters exposing Martian ground ice," Journal Geophysical Research, Planets, 119, no.1 (January 2014): 109–127, doi:10.1002/2013JE004482.
[62] Alfred S. Mcewen, et al., "Recurring Slope Lineae in Equatorial Regions of Mars." *Nature Geoscience* 7, no. 1 (January 2014): 53-58, accessed April 29, 2017, http://dx.doi.org/10.1038/ngeo2014.

an extended mission as of 2017, giving imaging options for potential landing sites and acting as a communications support for ongoing and arriving missions.[63]

Though most robotic missions to the Martin surface have been focused primarily on the sub-polar regions of the planet, Mars' polar regions hold answers to key questions concerning water and ancient history. NASA's *Phoenix* lander was designed to begin answering these questions. *Phoenix* was launched on 4 September 2007. It successfully landed in the Martian north polar region on 25 May 2008. The main goals of the *Phoenix* mission were to characterize the climate in the north polar region, to investigate the interaction of the north polar region with the atmosphere for at least 90 sols, and to study the geomorphology of the north polar region focusing on the role of water in shaping those regions.[64] *Phoenix* was successful in discovering ice on Mars, and it discovered that water ice sublimates on the Martian surface, as opposed to melting into water.[65] *Phoenix* successfully completed its mission and sent its last transmission on 2 November 2008, as the sun was setting below the horizon.[66] It was later found through orbital

Figure 4: Dodo-Goldilocks trench dug by Phoenix lander. White material is unknown, but most scientists at NASA believe this to be subsurface water ice. Source: NASA, JPL, https://www.jpl.nasa.gov/news/phoenix/images.php?fileID=13919

[63] "Mars Reconnaissance Orbiter."
[64] "Phoenix Mars Lander," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2007-034A
[65] Amy Shaw, et al., "Phoenix soil physical properties investigation," Journal of Geophysical Research. Planets, 114 doi: 10.1029/2009JE003455.
[66] "Phoenix Mars Lander."

imaging that the Martian ice fragmented the lander during the winter, causing irreparable damage to the solar panels.[67]

The next mission to Mars was launched by Russia on 8 November 2011. It was named *Phobos-Grunt* and was designed to collect a sample from the Martian moon Phobos and return it to Earth. *Phobos-Grunt* also had a hitchhiker orbiter, the Chinese *Yinghou-1*. The mission failed when the Fregat upper stage failed to fire, stranding the spacecraft in LEO. It re-entered the atmosphere in January of 2012.[68]

NASA, building upon the successful legacy of the MER program, next sent the largest rover to ever be sent to another planet, the Mars Science Laboratory, *Curiosity*. *Curiosity* is considered a precursor for an eventual human landing on Mars. It was launched on 26 November 2011 and arrived at Mars in August 2012.[69] Its landing was accomplished by another novel system, the "Sky crane" system which used retro rockets to slow the rover on its final descent before releasing it via tether onto the surface and crashing some distance away. NASA dubbed the landing system the "Seven Minutes of Terror."[70]

Curiosity had several missions:

> 1) determine the nature and inventory of organic carbon compounds; 2) inventory the chemical building blocks of life; 3) identify features that may represent the effects of biological processes; 4) investigate the chemical, isotopic, and mineralogical composition of the martian (sic) surface and near-surface

[67] Thomas H. Maugh, II, "Phoenix Mars Lander won't rise again," Los Angeles Times (May 25, 2010), accessed April 29, 2017, http://articles.latimes.com/2010/may/25/science/la-sci-mars-phoenix-20100525.
[68] "Phobos-Grunt," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2011-065A.
[69] "Mars Science Laboratory (MSL)," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2011-070A.
[70] "Sky Crane," NASA/JPL, n.d., accessed April 29, 2017, https://mars.nasa.gov/msl/mission/technology/insituexploration/edl/skycrane/.

geological materials; 5) interpret the processes that have formed and modified rocks and soils; 6) assess long-timescale (i.e. 4-billion-year) atmospheric evolution processes; 7) determine the present state, distribution, and cycling of water and carbon dioxide; and 8) characterize the broad spectrum of surface radiation, including galactic cosmic radiation, solar proton events, and secondary neutrons.[71]

Curiosity was highly successful in its mission. Using its data, it was determined that Mars could once have been hospitable to microbial life. The radiation environment of the Martian surface was characterized as well as soil composition, which has been used to design space suits NASA plans to send on their humans-to-Mars missions. It is, as of 2017, still active on the Martian surface, conducting extended paleontological studies, called taphonomy.[72]

Mars Orbiter Mission (MOM) or *Mangalyaan* (Sanskrit for "Mars voyager") was an Indian orbiter launched on 5 November 2013. It was the first craft ever sent to Mars by a rocket not of Russian or American construction, and made India the first country to reach Mars successfully with its first attempt. The orbiter was primarily a technology demonstration mission designed to develop mission architecture for future Indian interplanetary missions. As a secondary mission, it carried five science instruments meant to further knowledge of the planet. It is also the only mission designed to take full disc color imagery of the planet while orbiting, where ever other full disc image was taken on approach. Total cost of the mission is estimated at

[71] "Mars Science Laboratory (MSL)."
[72] John Grotzinger, "Habitability, Taphonomy, and the Search for Organic Carbon on Mars," *Science* 343, no. 6169 (January 24, 2014): 386-387, accessed April 28, 2017, doi:10.1126/science.1249944. Taphonomy can be defined as the study of processes which create fossils. In respect to astrobiology, taphonomy is the search for ancient microbial fossils in areas where life may have flourished.

$74 million, making it the least expensive successful interplanetary craft ever.[73] MOM remains on mission around Mars, and is to be extended as long as orbital correction fuel allows.

NASA's latest attempt to reach Mars was with the *Mars Atmosphere and Volatile EvolutioN* (*MAVEN*) orbiter. It was launched on 18 November 2013 and successfully entered Martian orbit on 22 September 2014.[74] The mission is designed to study the Martian atmosphere and its relationship to solar wind. It is hoped that *MAVEN* will help to determine the history of the Martian atmosphere and its loss over time. Scientists believe that the Martian atmosphere is only 1% as thick as it was in the past and that solar wind has played a role in that loss. After two years in orbit, the data from *MAVEN* was used to determine that water that sublimates on the Martian surface is broken into hydrogen and oxygen in the upper Martian atmosphere, where the solar wind strips it away. It was also determined that this process happens more rapidly at Mars' closest approach to the sun.[75] As of 2017, *MAVEN* continues its mission, and continues to make new discoveries, such as the presence of metal ions in the Martian atmosphere.[76]

The latest international mission which was launched to Mars was Russian/ESA join venture *ExoMars* Trace Gas Orbiter (TGO). It was launched on 14 March 2016 and successfully entered Martian orbit on 19 October 2016. Along with the orbiter was the *Schiaparelli* lander, a technology demonstrator. It was released from *ExoMars* on 16 October 2016.[77] The lander was

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[73] Madison Park, "India's spacecraft reaches Mars orbit ... and history," CNN, September 24, 2014, accessed April 29, 2017, http://edition.cnn.com/2014/09/23/world/asia/mars-india-orbiter/index.html.

[74] "Mars Atmosphere and Volatile EvolutioN (MAVEN)," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2013-063A.

[75] "NASA's MAVEN Mission Observes Ups and Downs of Water Escape from Mars," Astrobiology Magazine, October 22, 2016, accessed April 28, 2017, http://www.astrobio.net/also-in-news/nasas-maven-mission-observes-ups-downs-water-escape-mars/.

[76] Bill Steigerwald and Nancy Jones, "NASA's MAVEN Reveals Mars Has Metal in its Atmosphere," NASA, April 05, 2017, accessed April 28, 2017, https://www.nasa.gov/press-release/goddard/2017/metal-mars.

[77] "ExoMars 2016," NASA Space Science Data Coordinated Archive, last modified March 21, 2017, accessed April 29, 2017, https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2016-017A.

lost during entry due to a faulty inertial measurement unit reading causing it to believe that it was landed when it was about 3 km off the surface.[78] The TGO is still active, and is currently in an aerobraking orbit. It will begin science operations in late 2017.

Literature Review: Mars Exploration and Colonization Models

Robotic exploration of Mars, both from orbit and on the surface, is a necessary precursor to human arrival. The question of how humans make that journey has been studied since the 1950's. There have been an array of mission models and architectures developed internationally. Each has its own cost, though some were designed without a thought to cost and others were designed specifically to deliver the highest payout with the least investment. Each model has its own positive and negative aspects.

Das Marsprojekt

Wernher von Braun, a German scientist and rocketeer, wrote the first technological study of a possible Mars mission in 1948. It was written in his spare time using only a slide rule for calculations.[79] His work is seminal in that he produced the first study which showed that a journey to Mars was possible, yet almost prohibitively expensive. His calculations and design serve as a baseline for any future Mars missions.

Many researchers and mission planners call the *Marsprojekt* design the "Battlestar Galactica"[80] mission design due to von Braun's architecture calling for a fleet of spaceships to make the journey. His plan called for the Martian fleet to be built on orbit with the use of 46 shuttle orbiters. These orbiters would fly 950 missions over an eight-month period, launching

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78 Peter De Selding, "ESA: Mars lander crash caused by 1-second inertial measurement error," SpaceNews.com, November 23, 2016, accessed April 28, 2017, http://spacenews.com/esa-mars-lander-crash-caused-by-1-second-inertial-measurement-error/.

79 Wernher von Braun, *The Mars Project* (Urbana, IL: University of Illinois Press, 1953), xv.

80 *Battlestar Galactica* is an American television, film, and print media franchise in which fleets of large ships are used to move between planets.

from Johnson Island in the Pacific Ocean. The fleet would consist of 10 spacecraft of 372 tonnes each. Of these ships, 3 would be cargo ships, carrying the Mars landing craft and consumables. The other 7 would be crew habitation ships. The total crew for the mission would be "no less than 70 personnel."[81]

The mission architecture called for these ships to leave Earth's gravity well along a Hohmann transfer orbit, terminating at Mars approximately 260 days after departure.[82] Once in Martian, or areocentric, orbit, the crew would conduct remote analysis of the planet, its atmosphere, and potential landing sites. At the time of his writing, it was thought that only the Martian poles would be flat enough to allow for the landing of gliders on the surface, therefore the poles would be given priority over equatorial regions which were thought to be too rocky to allow for a landing. Only one of the "landing boats" would land at one of the poles of the planet. This would allow the crew to land and then make their way to the equatorial region, where they would prepare a runway for the other two landing craft. The initial lander would have only enough fuel on board to successfully land, and would be left on Mars at the completion of the mission. The other landing craft would have enough fuel to land and return to orbit after completion of the on-planet portion of the mission. When returning to orbit, the landers would shed their wings and landing gear, leaving only the torpedo shaped portion of the craft to ascend to orbit. The mission plan called for 400 days of surface operations for 50 of the crew.

The *Marsprojekt* design was the first attempt at translating the technological needs of a Mars mission into the language of physics and rocketry. It was a grandiose plan, brimming with optimism at what humanity could accomplish. However, from the perspective of mission planners who must operate within budgets and realistic timelines, the plan was and continues to

[81] Von Braun, *The Mars Project*, 3.
[82] Ibid, 64.

be entirely unwieldy. Even the plan to run 950 shuttle missions using 46 space shuttles over an eight-month period was entirely too optimistic, as was shown in the American Space Shuttle program of 1982-2011. As written, the von Braun plan would require 4 shuttle launches per day on average. Even under the most ideal circumstances, the US Shuttle program required "several weeks" of post-launch maintenance and repair of the launch pad, this, added to the 30-day pre-launch pad preparation, means that a single pad could only conduct one launch every two months.[83]

At the time of the release of *Das Marsprojekt* man had not yet reached space. Where the science and science-fiction communities might be awed by the prospect of travel to Mars, politically and technologically at the time of the release of von Braun's work the project was decades in the future.

Mars Direct

In contrast to the grandiose and expensive *Das Marsprojekt*, Mars Direct is thrifty and bare-bones. This mission architecture was proposed in 1996 by a former senior engineer for Lockheed Martin Astronautics, Dr. Robert Zubrin, who left Lockheed and started his own company, Pioneer Aerospace, which conducts research in new technologies with a goal of proving concepts for a Mars mission. Mars Direct proposed using existing launchers and technologies, making it inexpensive. It also used conjunction class trajectories, which provided a "free return" for the spacecraft in case of emergency while in transit. It was designed to be scalable and with many redundancies, allowing for the expansion of exploratory missions into full blown colonization. Finally, the mission design called for in situ resource utilization (ISRU), particularly in relation to fuel processing. This meant that planners would be able to get "more

[83] Stephen Siceloff, "Shuttle Liftoffs Require Precision Launch Pad," NASA.gov, April 27, 2011, https://www.nasa.gov/mission_pages/shuttle/flyout/launchpadflyout.html (accessed 5 April 2017).

bang for their buck" in sending unfueled return vehicles, ergo being able to send more supplies and payload before the arrival of the first explorers.

The Mars Direct mission concept began with the Earth Return Vehicle (ERV). The ERV would be launched aboard an Ares (now SLS) rocket at a time when Earth is in conjunction with Mars. The ERV would weigh 45 tonnes including a payload of supplies, a small nuclear reactor on an automated rover, several smaller scientific rovers, and a chemical processing plant. The ERV's fuel cells capable of holding around 100 tonnes would be sent empty except for 6 tonnes of liquid hydrogen which would be used to generate fuel on Mars.

When the ERV lands at Mars, the rover with the nuclear reactor will roll out and to a safe distance from the ERV and begin supplying power to the ERV habitation module and the chemical plant. The hydrogen will be reacted with the Martian atmosphere, which is 95% composed of carbon dioxide, in a Sabatier reaction as follows:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

In this reaction, also called methanation, hydrogen reacts with carbon dioxide to produce methane and water. The methane would be stored as rocket fuel. The resultant water would then be stored for consumption, or would be electrolyzed to produce hydrogen and oxygen. The oxygen would be stored for consumption or as fuel oxidizer and the hydrogen would be put back into the chemical processing plant as seed to continue making methane. Using this simple reaction which has been used industrially since the late 1800's, the ERV would produce all the fuel needed to return to Earth with a relatively small amount of hydrogen as seed.[84]

After a thirteen-month fueling period, the ERV would undergo a telerobotic certification process and the scientific rovers would begin the next step of the mission. They would be sent

[84] Zubrin, *Entering Space*, 153.

out to explore and map the immediate vicinity of the landing area. Once a suitable location for the habitation module (the HAB) has been selected, a radio beacon would be set up to guide the first explorers to the landing site.[85]

At the next conjunction launch opportunity, two launches would take place. The first would be identical to the original ERV launch. The second launch would propel the HAB, along with the crew, to Mars. The HAB would stand about 5 meters high and measure 8 meters in diameter. It would contain a closed-loop life support system and rations (fresh and dehydrated) for three years, plus emergency dehydrated rations. The HAB would consist of two decks, each with about 1,000 square feet of living space for the four astronauts. It would also carry a pressurized rover with a methane/oxygen combustion engine. After launch, the HAB would separate from the spent third stage of the rocket, though remain connected by a tether 330 m long. The third stage would then fire a small motor to revolve the combination at 2 revolutions per minute, simulating Martian gravity while in transit.

After 180 days, the HAB will arrive at Mars. The crew would then land the HAB at the ERV 1 landing site. If that landing site is missed, there are three options which could be used to assure the availability of Earth return. The pressurized rover accompanying the HAB would have been designed for a 1,000-km one-way trip, so long as the HAB is within that distance to ERV 1, the crew would have access. The second option is ERV 2, which would still be en route to Mars. ERV 2 can be redirected to land near the HAB to allow for return after the thirteen-month fueling period. Finally, the crew will have been sent to Mars with a three-year supply of food. They could potentially "tough it out" until either rescue or resupply could be sent.[86]

[85] Robert Zubrin and Richard Wagner, *The Case for Mars: The plan to settle the Red Planet and why we must* (New York: Free Press, 2011), 6-7.
[86] Ibid, 9-10.

After landing, the crew will spend 500 days on the Martian surface conducting experiments, exploring, building facilities such as greenhouses, etc. After their tenure on the surface, they will board the ERV and return to Earth on another 6-month voyage. As the splash-down on Earth, another crew will be entering their final preparations to make the same voyage. Once HAB 2 and its crew reach Mars, the plan calls for them to land some 800 km away from HAB 1. If all goes to plan, this would allow the next crew to access the previous HAB(s) to monitor ongoing science experiments, access stored fuel, leftover rations, etc.[87]

The Mars Direct plan has many aspects which appeal to mission planners. Foremost is redundancy. For every step of the Mars Direct plan, there is a backup. If there is an emergency in transit to Mars, the plan uses a trajectory that gives the crew a “free-return” if necessary. While this would be a two-year round trip journey, it is appealing because it uses no fuel, thus the name free-return. If the HAB fails to land close to the ERV, there are options as previously mentioned.

The next aspect which would appeal to mission planners is sustainability. As opposed to the *Marsprojekt* plan, Mars Direct is very lean. Where that plan called for nearly 1,000 launches in rapid succession, the Mars direct plan calls for two heavy-lift launches every two years, or an average of one launch per year. This is well within current NASA budgetary restraints. The plan also does not require the construction of all new launchers or construction of massive ships on orbit. Mars Direct only requires the use of a heavy-lift rocket. As of 2017, NASA is developing the Space Launch System (SLS), slated for its first launch in October 2018, which would be capable of producing the required lift. If a private venture wished to conduct a Mars Direct-type plan, the Falcon Heavy launcher, slated for its first launch in 2017, would be available for purchase.

[87] Ibid, 12-13.

Finally, and perhaps most importantly, the Mars Direct plan calls for the entire crew to visit the surface for 500 days. While this may seem a dangerous decision without a fail-safe, it extends surface time while reducing radiation exposure for the crew. If a portion of the crew were required to remain on orbit, a surface time of thirty days would be the maximum allowable, because the crew on orbit would lack the protections from radiation that the planet gives. If the entire crew visits the surface, stay time can be extended indefinitely. If there is an emergency that requires immediate return to orbit, that can be accomplished using the already-fueled ERV. The 500-day surface stay time also allows for a much more efficient mission with the possibility of greater scientific benefit. Where, if stay time were only 30 days, the public and scientists might find the cost of the mission hard to swallow for such a short time on the surface.

Detractors of Mars Direct point out that the use of conjunction class trajectories would require the crew to remain in space for longer, which would increase their radiation risk.[88] However, as Zubrin points out, the real differences between conjunction- and opposition-class are that conjunction would require extended surface stay, while opposition would require a flyby of Venus on the return to Earth. Much to the contrary of detractors, opposition-class missions would require a total of 610 days of space transit time while conjunction-class missions would require 360 days. The true appeal of opposition class missions is that with the reduction in surface time, about 10 months of time off earth is cut from the schedule, bringing home the crew in 640 days as opposed to 910 days. Finally, Zubrin proposes that opposition-class missions are costlier as they require a higher delta-v (change in velocity required for the mission) resulting in higher fuel costs.[89]

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[88] Erik Seedhouse, *Martian Outpost* (Chichester, UK: Praxis Publishing, 2009), 36.
[89] Zubrin, *Case for Mars*, 91 (Table 4.1).

Aldrin's *Mission to Mars*

Dr. Edwin "Buzz" Aldrin is a true American hero, and a hero to the cause of space exploration. His work in rendezvous orbits and space-walking practice were essential to placing humans on the moon in the 1960's. He was also present at *Mare Tranquillitatis* on July 20, 1969 when Neil Armstrong became the first man to walk on the moon. Aldrin was the second. He once again put his talented mind to use in developing a Mars exploration model which would place humans on Mars by 2035.

His model is explicated in his book *Mission to Mars*. In this work, he details his long-term plan for space exploration, with Mars being the endpoint. His plan calls for a multi-lateral international approach which would first visit the moon and the asteroids, terminating at Phobos and then Mars. Major points of his plan call for the use of "Aldrin cycler orbits" which he devised while attempting to define cycler orbits for an Earth-Moon system. These orbits make use of minimal fuel and offer free return to Earth and Mars on a regular cycling basis. Aldrin envisions a pair of cyclers operating on complimentary orbits to allow for a 5-month voyage on both the outbound and inbound legs of the trip.[90]

Dr. Aldrin's plan begins with his "old stomping grounds," the moon. He envisions a consortium that exists to lessen the cost of travel to the moon for those countries that wish to go. In theory, this consortium would be a collection of all the technical and scientific data that has been gathered in the past. It would be an international venture. He sees America as a leader in developing this consortium and envisions America being able to assist with lunar exploration

[90] Buzz Aldrin, *Mission to Mars: My vision for space exploration* (Washington, D.C.: National Geographic, 2013), 33-39 and 195-99.

efforts by constructing orbiting bases at the various Earth-moon Lagrange points.[91] In his vision, America would not waste precious money for Martian missions by returning to the moon, but would ensure a return to the moon by assisting other countries and private interests.[92]

The next major part of Dr. Aldrin's plan calls for missions to asteroids. First, he points out that missions to asteroids will give NASA or any other agency practical experience in working with the most difficult of situations. Asteroids lack gravity, thus provide an excellent test bed for new technologies which would be developed to allow astronauts to work and live on their surface. Dr. Aldrin then gives two compelling reason for travelling to asteroids. The first is seated in the fact that asteroids have struck the earth with some regularity and given no change to the situation, will strike again in the future. Dr. Aldrin proposes that human journeys to asteroids will be key to resolving this issue, possibly once and for all.[93] The second reason that humans will go to asteroids is for profit. An average asteroid with average characteristics contain billions of dollars' worth of materials. If humanity were to learn to harness these rocks in space and process those materials, the entire human race could benefit from this.[94] Finally, a mission to an asteroid would be a sort of "practice run" for an eventual mission to Mars' closest neighbor, Phobos.[95]

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[91] Lagrange points are points in space where the combined gravities of two large bodies will "counteract" one another allowing a third, smaller body to maintain an orbit indefinitely while using no fuel. For any two-body system, there exist five Lagrange points (L-points).
[92] Aldrin, *Mission*, 101-13.
[93] Ibid, 115-38.
[94] Ibid, 138-43.
[95] Ibid, 115-43.

Phobos is the closest object to Mars, with an orbit of 9,377 km above the Martian surface.

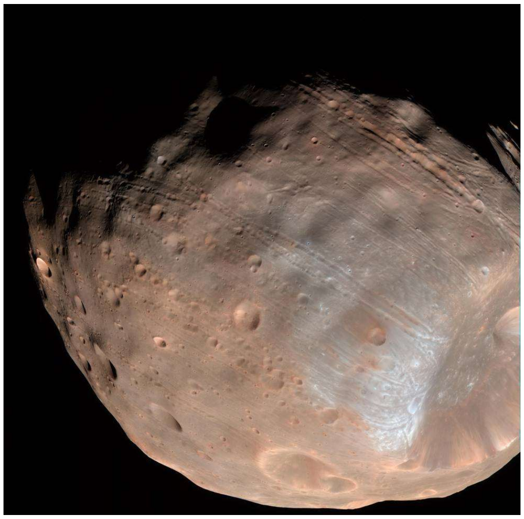

Figure 5: Phobos in full color as imaged by the Mars Reconnaissance Orbiter. Source: NASA, JPL-Caltech, https://www.nasa.gov/feature/goddard/phobos-is-falling-apart

It orbits Mars once approximately eight hours and is tidally locked with the planet. It is the larger of the two Martian moons at 26.8 km in diameter. In Dr. Aldrin's eyes, this would make it the perfect precursor mission to a human Mars mission. In the Aldrin plan, a crew of astronauts would build a base of Phobos from which to telerobotically set up a Mars base camp on the surface. This would allow for more rapidity in rover movement and real-time reaction times by the rover operators, as these times have historically been long due to long communication times between Mars and Earth. Finally, Dr. Aldrin argues for using Phobos (or Deimos) as a contamination barrier for forward and backward planetary protection. Any travelers going to Mars would first visit the Phobos base to decontaminate and any samples originating from Mars would be studied on Phobos until it is proven that no Martian biologics are present.[96]

The final leg of the trip to Mars in Dr. Aldrin's plan is to send a team from Phobos to the Martian surface. This mission would not only place humans on Mars, but would become a precursor to "homesteading" the planet and colonization. Dr. Aldrin argues in favor of humans instead of robots, because humans are adaptive, insightful, perceptive, and quick moving in comparison. He envisions humans to Mars missions beginning in 2033 and 2035 due to favorable astrodynamics for fuel savings and to limit radiation exposure for the crew.[97]

[96] Ibid, 145-56.
[97] Ibid, 158.

Dr. Aldrin's plan is different than many of the plans that have been proposed in the past. Few plans include the use of the Martian moons as staging areas for the main mission. It is also different in that it assumes international cooperation on a large scale. Dr. Aldrin is a veteran of the only program which has ever sent humans to another world, as such, he is possibly the best source of worthy ideas for future interplanetary missions. He and Zubrin agree on many aspects, including asteroid precursor missions, but they diverge on the scope of how large a ship would be necessary and the investment required to complete the mission. Where Zubrin sees small missions and ships, Aldrin has conceptualized several cycler trajectories with differing inbound and outbound times. If these were to be used most efficaciously, there would be a requirement for at least 10 ships traversing the solar system constantly.[98] While this plan would make sense once a full-scale colonization effort is in effect, for humanity's first voyages to Mars, this would prove cost-prohibitive. Dr. Aldrin's plan would be less than the scale of Dr. von Braun's, but would be massive nonetheless and would require large construction projects in orbit. This is something that has never been done, with the notable exception of the ISS, which took many years and an investment of a total of $150 billion to build.[99]

A mission to Mars will be a human mission, nationalities have no real part in it. However, both points can be used as detractions from his plan. The use of large scale international cooperation in space has been seen in only one project, ISS. However, this project does not even include all nations with human spaceflight capabilities, as China is notably absent from this program. CNSA and RFSA often work together on space projects. NASA and RFSA also work together. However, there has never been a project in which all the "big three" agencies

[98] Ibid, 195-99.
[99] Claude Lafleur, "Cost of US piloted programs," *The Space Review*, March 8 2010, accessed May 26, 2017, http://www.thespacereview.com/article/1579/1.

have collaborated. This can and may change in the future, but it would require an immense amount of trust between former enemies, something that seems to be very far away.

As for the use of Phobos or Deimos as staging areas, there have been studies conducted by JPL and Lockheed which have shown that this is an exceptionally good idea.[100] However, these missions should be preceded by missions to asteroids. The only mission ever proposed to do this, NASA's Asteroid Redirect Mission (ARM) was cancelled due to a lack of political will and funding by the US Congress.[101] However, if SLS and Orion move past the two planned missions which they will fly in 2018 and 2021, the hardware would be available to attempt such a mission.

NASA's Journey to Mars

NASA has been in an upheaval mode since President George W. Bush laid out his Vision for Space Exploration in 2004. This upheaval continued during the tenure of President Barack Obama, as he cancelled the star of the VSE program, *Constellation,* in 2010. His presidency also saw the close of the Space Shuttle era in 2011. NASA's new plan, the Journey to Mars (JtM), consists of a new capability driven roadmap to Mars. In this capability-driven approach, a definite end-goal is only suggested at and capabilities would be developed and uses for them would be derived later. While this lacks a definitive goal, it has given hope to many scientists about America's long-term goals in space.

JtM begins with the completed ISS. The station was started in 1998 with the Russian *Zarya* module. Thirteen years later, the final NASA module, the Permanent Multipurpose

[100] Ibid, 157-60.

[101] Marcia S. Smith, "House Appropriators Reject Asteroid Redirect Mission, Want Astronauts on Moon – UPDATE," Space Policy Online, May 24, 2016, accessed April 29, 2017, http://www.spacepolicyonline.com/news/house-appropriators-reject-asteroid-redirect-mission-want-astronauts-on-moon.

Module (PMM), was mated to the station by STS-133 crew. Planned construction of the Russian side of the station continues, and is scheduled to be completed in the 2018 timeframe. As an analog to a future Mars journey, ISS serves as a test-bed for new technologies and for research into the effects of microgravity on the human body. Some of these research efforts have even gotten international attention, such as the "Year in Space" completed by astronaut Scott Kelly and cosmonaut Mikhail Korniyenko in March 2016.

With ISS as the test-bed for emerging technologies for a Martian mission, the next step for NASA will be the Space Launch System (SLS) program. SLS is the derivative of the cancelled *Constellation* program Ares I and V rockets and legacy Space Shuttle hardware. The SLS is planned to have three block designs to be tailored for specific mission requirements. The first iteration, SLS Block I, is designed to deliver 70 tonnes to LEO. The second iteration, SLS Block IB, will be capable to delivering 105 tonnes to LEO. The final proposed design, SLS Block IIB, is congressionally mandated to be capable of lifting 130 tonnes to LEO. Missions for each iteration have been proposed, but only two missions have been approved, using the Block I and IB configurations.

With the SLS launcher being the most powerful heavy-lift rocket ever designed, a new capsule system would be required to take advantage of that power. Enter *Orion*. *Orion* is a crew module design lifted directly from the *Constellation* program. *Orion* is designed for a crew of 2 to 6 personnel. It is 5.2 meters in diameter, 3 meters tall, and uses the *Apollo*-era 57.5-degree frustum shape. It is designed with a capability to support a crew for up to 21 days, with a quiescent mode capable of supporting up to six months of spaceflight. Launch weight of the *Orion* will be approximately 8,900 kg. *Orion* itself is the result of international collaboration as the Service Module is being designed by ESA affiliated companies. While the main propulsion system and some associated circuit cards are being developed by Lockheed.[102]

SLS and the JtM program have come under fire since their inception by many in the space community, including former NASA officials. The first major objection of the JtM plan is that it will be expensive. While previous panels and commissions have placed the cost of a Mars mission anywhere between $80 billion to $1 trillion, it is not easy to establish the true cost of JtM because the program is very open ended and flexible. The best estimate to date was determined by a 2014 expert panel at the Human to Mars Conference, which concluded that a 20-year program terminating in a Mars mission would cost approximately $80 to $100 billion, which is within NASA budget constraints.[103] Several factors make the NASA model more cost restrictive than other comparable and more efficacious models. First, NASA is a government agency, which already makes programs more expensive due to certain factors, including competing programs and centers, pet-project priority, etc. Second, NASA is a bureaucratic institution. With that bureaucracy comes increased personnel, ergo increased costs. Finally, NASA, as a government organization, is more risk averse than a private company would be.

The second major objection from the scientific community for JtM is the program architecture. In SLS, NASA has dedicated itself to building a rocket from existing parts and technologies, not necessarily a negative aspect. However, the job of taking parts and pieces from several different programs dating back to the 1960's and building a new rocket has proven costly. The quoted cost for flying an SLS mission is between $600 million and $1 billion.[104] Add

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[102] "Lockheed Martin Delivers Orion Spacecraft To NASA Kennedy Space Center," Lockheed Martin, July 2, 2012, accessed May 26, 2017, http://www.lockheedmartin.com/us/news/press-releases/2012/july/lockheed-martin-delivers-orion-spacecraft-to-nasa-kennedy-space-.html.

[103] Marc Kaufman, "A Mars Mission for Budget Travelers," *National Geographic*, April 23, 2014, accessed April 29, 2017, http://news.nationalgeographic.com/news/2014/04/140422-mars-mission-manned-cost-science-space/.

[104] Dale Skran, "Battle of the Colossi: SLS vs Falcon Heavy," *The Space Review*, April 27, 2015, accessed April 29, 2017, http://www.thespacereview.com/article/2737/1.

to this an estimate of annual maintenance costs of $2.5 billion, based on the Shuttle program, and the price tag for SLS begins to rise substantially and quickly. When the result of the launch is an expendable rocket and capsule, that cost is rather high, especially when newer launch systems like the Falcon 9 and the future Falcon Heavy promise a large amount of reusability and cost reductions.[105]

The third objection, and a large point of contention, is that on its very surface, the SLS/*Orion* system is not designed for a mission to Mars, it is designed to fly to the moon.[106] While the moon remains a beneficial target for space exploration, it is not a necessary or even cost effective step on the way to Mars. While the hardware used for a Mars mission would be perfectly capable of making a lunar voyage, the converse is not true, as lunar missions do not require as rugged a capsule as Mars missions will. In looking to return to the moon, NASA and the Presidential administration must be wary not to lose sight of Mars.[107]

JtM does serve a positive purpose in that it has given the public a sense of what it will take to get to Mars. It has spurred new innovations and will continue to do so for the foreseeable future. While the cancellation of the Shuttle program is seen by many as a negative aspect of President Obama's National Space Policy of 2010 (NSP2010), it was necessary for the future of space exploration. The Shuttle program was designed in the 1970's to keep the tens of thousands of Americans who had worked on the Apollo program gainfully employed until the next major exploration push.[108] With the Shuttle program cancelled, mission planners are forced to find new ways to accomplish their goals. One major advancement has been the move toward commercial

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[105] Ibid.
[106] Eric Berger, "Make Mars great again: Can the 2016 election save NASA's Journey to Mars?" ArsTechnica, April 12, 2016, accessed April 29, 2017, https://arstechnica.com/science/2016/04/make-mars-great-again-can-the-2016-election-save-nasas-journey-to-mars/.
[107] Zubrin and Wagner, *Case for Mars*, 147-50.
[108] Zubrin, *Entering Space*, 30.

space enterprises such as Orbital ATK and SpaceX for launch to orbit. Where in the 1980’s and 1990’s there were few options for launch, now the marketplace has expanded to a point where competition for launches is driving down costs. The winner in that scenario is humanity. Decreasing launch costs will bring about more launches, new technological developments, and access to space for more countries. Moreover, the decrease in launch costs will begin a new era of commercial development of near-earth and eventually cis-lunar space. This will lead to a new era of commercial prosperity.

Mars Base Camp

Lockheed Martin (Lockheed) has been with NASA since the beginning, in one form or another.[109] They are the prime manufacturer of *Orion*, NASA’s proposed crew-rated workhorse for the future. In 2016, Lockheed made a proposal which surprised the industry, a crewed Mars mission in the 2028 timeframe. The plan is straight forward: construct a deep space outpost in cis-lunar space and then use an engine to put it on a Mars trajectory. It name is Mars Base Camp (MBC), and the plan is to send astronauts to orbit Mars in the 2020’s to prepare the way for human landings in the 2030’s.[110]

MBC would be constructed in cis-lunar space. It would be comprised of at least two *Orion* capsules connected via a system of habitation modules that are yet to be developed. Lockheed proposes that six humans make the journey. The plan would have the entire outpost orbit Mars for a 10 to 12-month timeframe before returning to Earth.[111] NASA has yet to fund or endorse the project.[112]

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[109] “Powering the Space Race,” Lockheed Martin, accessed May 27, 2017, http://www.lockheedmartin.com/us/100years/stories/space-race.html.
[110] “Mars Base Camp,” Lockheed Martin, 2016, accessed April 29, 2017, http://www.lockheedmartin.com/us/ssc/mars-orion.html.
[111] Ibid.
[112] Vikas Shukla, “Lockheed Martin to Send Six Astronauts to Mars By 2028,” 2016, http://www.valuewalk.com/2016/05/lockheed-martin-astronauts-mars-2028/.

MBC is a completely different approach than most. It relies heavily on the SLS/*Orion* system, which has yet to fly. The habitation modules are also yet to be developed, but companies such as Bigelow Aerospace could find a role for themselves in the plan. The plan harkens back to sending humans into lunar orbit on *Apollo 8* ahead of putting "boots on the ground," an approach that NASA has favored in the past as a precursor for crewed landings. Overall, MBC is the kind of outside of the box thinking that will be required for sending humans to Mars and returning them safely. As a bonus, the MBC plan could be used to land on Phobos and/or Deimos, which would allow for greater understanding of those bodies as well.

There are some great selling points for MBC. It uses technology already in existence. It will call for at least four SLS launches, filling a manifest which is continuously threatened by budget cuts. It will put humans in Martian orbit earlier than previously proposed. It allows for direct human observation of the Martian surface from a close range, allowing the crew to pick out a handful of potential landing sites for the first crewed mission to Martian soil. Finally, it is a mission that is well outside of the bounds of anything that has been done before, but not so far outside that entirely new technologies must be developed to make it happen.

As far as objections, it requires heavy use of the SLS system, which, as previously discussed, would be an expensive prospect. There would be developmental costs, but if NASA continues to use commercial suppliers and services those costs could be capped. Finally, though Lockheed mentions radiation protections in their announcement, the protection system of the *Orion* is still unproven in deep space. If they truly want to provide the kind of protection they are proposing, one of the *Orion* capsules would need to be surrounded by the mission fuel while in transit to and from Mars. This is not impossible, but would complicate the docking portion of construction. In general, when it comes to designing a mission such as one to Mars, no idea is a bad idea until it is proven to be so. MBC has brought a new spotlight onto non-standard mission types and ideas.

Andy Weir's *The Martian*

Though it is a work of fiction, Andy Weir's novel about an astronaut stranded on the surface of Mars, *The Martian*, became a best-seller, became an Academy Award nominated movie, and put focus on a human Mars mission. Most of the science of *The Martian* is sound, with a few artistic liberties taken by Weir. As part of his process for writing *The Martian*, Weir spent time with people from JPL to discuss Mars mission models.

The actual mission model used in *The Martian* is a hybrid of several existing plans. It uses a large "Battlestar Galactica" style autonomous ship, *Hermes*, to transport crews to and from Mars. Once in Martian orbit, the crew boards a Mars Descent Vehicle (MDV) to transfer to the surface for a 30-day mission. Prior to the crew's arrival, a Mars Ascent Vehicle (MAV) with supplies was delivered, using technologies such as Mars Oxygen ISRU Experiment (MOXIE) to make effective use of the resources available, making rocket fuel and oxygen out of the Martian atmosphere. After a 30-day trip to the surface, the crew board the MAV and launch back to the *Hermes*, which then uses its ion engines to bring the crew back to Earth. From the perspective of the book, the Mars program is run exclusively by NASA, with some international cooperation in crew selection.

Both NASA and Weir have stated that a real Mars mission would be very dissimilar to the book. For instance, astronauts will most likely land on the Martian moons prior to landing on the planet itself. Weir has stated that NASA will most likely not be the only agency involved and the real mission to Mars is much more likely to be conducted by a multi-national corporation.

There is also potential for a commercial firm such as SpaceX to lend its support.[113] While Weir's vision has inspired the world and shown what could be accomplished, it is simply a fantastical tale of one man's struggle for survival in the harshest of situations.

Mars One

Private space exploration has been an idea which has inspired science fiction writers for many years. The Dutch company Mars One seeks to make this a reality. The company made headlines in 2012 when it announced that it was planning a privately funded mission to put humans on Mars by 2023.[114] More headlines were made in September of 2013, when their international astronaut recruitment campaign garnered 202,586 applicants from over 140 countries.[115] Mars One proposes a novel plan and funding campaign to make the mission happen. However, these are some of the same attributes detractors claim will be Mars One's downfall.

Mars One's plan begins by removing the return trip for the astronauts. By removing the need for equipment for the return of the astronauts, Mars One hopes to cut the cost of traveling to Mars to about $6 billion. This makes Mars One not so much an exploration plan, but more of a settlement plan. Their planning or "roadmap" began in 2013 when they held the first open astronaut application process. The next step will be the beginning of astronaut training, which is scheduled for 2017.[116] Astronaut training was originally scheduled to run through the first crew

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[113] Brian Fung, "NASA and the author of 'The Martian' tell us exactly how we'll get to Mars," The Washington Post, May 18, 2016, accessed April 29, 2017, https://www.washingtonpost.com/news/the-switch/wp/2016/05/18/nasa-and-the-author-of-the-martian-tell-us-exactly-how-well-get-to-mars/?utm_term=.90c10d5ba178.
[114] "Mars One will settle men on Mars in 2023," Mars One, May 31, 2012, accessed May 8 2017, http://www.mars-one.com/news/press-releases/mars-one-will-settle-men-on-mars-in-2023.
[115] "Over 200,000 apply to first ever recruitment for Mars settlement," Mars One, September 9, 2013, accessed May 8, 2017, http://www.mars-one.com/news/press-releases/over-200000-apply-to-first-ever-recruitment-for-mars-settlement.
[116] "Roadmap," Mars One, accessed April 29, 2017, http://www.mars-one.com/mission/roadmap.

launch in 2022-23, but delays in funding and technology development have pushed back the first crewed launch until 2031.[117]

The actual launch architecture of the plan begins in 2022 with a technology demonstration lander. This would be followed with launches of communications satellites and landers at every Hohmann transfer window. The 2029 opportunity would see the entirety of the outpost structure being launched along with semi-autonomous robotic builder-rovers. The outpost would be completed and tested as structurally sound and ready for habitation in 2030. Meantime, an on orbit construction crew would piece together the habitation module with the landing module and the necessary fuel modules in Earth orbit. After the construction phase, the first Mars crew would ferry to the spaceship and begin their journey in 2031. The plan currently calls for the first crew to arrive at the already completed colonization outpost on Mars in 2032. Thereafter, a new crew and habitation module would launch at every opportunity, landing the modules close enough to one another that a complex of modules would be developed and grow with each successive set of settlers.[118]

While the Mars One plan has generated some publicity, it is bound to fail. First, the Mars One plan is estimated to cost $6 billion. Industry experts agree that this number is undervalued by a substantial amount. Engineering graduate students at MIT found that the valuation of the Mars One program does not consider development, operations, or spare parts costs, which would become increasingly unwieldy as more settlers were sent to Mars.[119] Moreover, the funding plan which Mars One has attempted to put in place relies on media sponsorship for a reality television type experience. While Mars One hopes to raise the capital for the mission through this

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[117] Ibid and Mars One, “Mars One will settle men on Mars in 2023.”
[118] Mars One, “Roadmap.”
[119] Sydney Do, et al., "An Independent Assessment of the Technical Feasibility of the Mars One Mission Plan," 65th International Astronautical Congress, Toronto, Canada, September 29-October 3, 2014.

sponsorship, media analysts state that the $6 billion which the company seeks is out of touch with the reality of broadcast sponsorship. Even under the best sponsorship deals, the franchise would fall "several orders of magnitude short" or their goal.[120] Even those selected as settlers by Mars One find the company ethos to be "dangerously flawed."[121] "[One selectee] expressed many concerns, ranging from inaccurate media coverage (there were only 2,761 applicants, not 200,000) to Mars One's psychological or psychometric testing (or lack thereof) to how leading contenders earned their spot (he says they paid for it)."[122]

SpaceX's Mars Colonization Transport

Space Exploration Technologies (SpaceX) has been turning heads and turning the world of rocketry upside down since its inception in 2002. SpaceX was founded by billionaire Elon Musk with the intent of "enabling people to live on other planets."[123] To enable that goal, SpaceX has focused on lowering the cost of launch by making their launchers reusable. By lowering the cost of launch to LEO, SpaceX hopes to enable a public-private partnership to make trips to Mars in the future.[124]

Elon Musk gave a much-anticipated speech on September 27, 2016, at the 67th International Astronautical Conference. In this speech, he laid out SpaceX's Mars colonization plan. The first part of this plan is dependent upon full reusability of the entire spacecraft and launcher, a goal the SpaceX has made great strides towards achieving. Then, Musk proposes

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[120] Jonathan O'Callaghan, "Why Mars One will NEVER get off the ground: Lack of funding, no spacecraft and no rocket makes mission a 'fool's dream', claim experts," *Daily Mail*, February 19, 2015, accessed May 9, 2017, http://www.dailymail.co.uk/sciencetech/article-2960096/Why-Mars-One-NEVER-ground-Lack-funding-no-spacecraft-no-rocket-makes-mission-fool-s-dream-claim-experts.html.
[121] Janet Fang, "Mars One finalist announces that it's all a scam," IFL Science, March 22, 2015, accessed May 9, 2017, http://www.iflscience.com/space/whats-going-mars-one/.
[122] Ibid.
[123] "About," SpaceX, n.d., accessed May 9, 2017, http://www.spacex.com/about.
[124] Elon Musk, "Making humans a multiplanetary species" (lecture, 67th International Astronautical Congress, Guadalajara, Mexico, September 26-30, 2016), accessed May 9, 2017, http://www.businessinsider.com/elon-musk-mars-speech-transcript-2016-9/#-1.

designing and constructing a rocket larger than anyone has ever envisioned. The "Mars rocket" will be capable of placing 300 to 550 tonnes in LEO with each launch. This is accomplished with the use of 42 Raptor engines on the first stage, delivering a thrust of 13,000 tons. An excellent comparison would be to the Saturn V rocket, the largest ever launched, which had 5 main engines and produced a thrust of 3,579 tons. The Saturn V was capable of lifting 135 tonnes to LEO.[125]

Next, Musk laid out the plan for his "Mars vessel" to be launched from earth with an empty fuel tank and be fueled on orbit by boosters. Money is saved at this stage by reusing the launch hardware to launch the vehicle and the fuel, with several fuel launches needed for each spaceship on orbit. Once the ships are fueled and crewed with approximately 100 people, they will head to Mars, where the crew will land and deploy living quarters and laboratories to work in. After an unspecified length of time, during which the ship will be refueled using methanation-electrolysis of Martian water ice and atmosphere, the ship will launch from the Martian surface and return to Earth to be refueled and sent back to Mars.[126]

Musk admits that the development costs for such a plan are going to be huge. His published timeline has the company already developing propulsion and structures for the launcher and spaceship. The first Mars mission on the new SpaceX ship would take place in the mid-2020s. By the time of the conference, SpaceX had tested the Raptor engine and had built the first carbon-fiber cryogenic fluid storage tank for testing.[127]

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[125] Ibid.
[126] Ibid.
[127] Ibid.

Musk's plan has a good chance of succeeding. It takes advantage of, and builds on, previous experiences that SpaceX has had with the Falcon 9 rocket, particularly with reusability. Though Musk tends to speak in large numbers ("1000's of spacecraft"), on the scale of a single or even several ships, SpaceX could successfully mount a human mission to Mars. If Elon Musk sees the Mars program through, he envisions a future of sending humans to the outer solar system as well.[128]

Analysis

Criteria Selection

Any human mission to Mars must meet three requirements to be successful. First, the mission plan should take the health of the crew into consideration, applying active and passive mitigations where needed. Second, the mission must be cost effective. Third and finally, the mission must be sustainable, leading to colonization efforts in the years after exploration. If these three criteria are met, humanity will be on its way to what Zubrin deems a "Type 2 Civilization," one having control of its star system.[129]

Crewmember Health

Going to Mars will not be easy. Even if a mission were to be perfectly executed, there will be substantial risk to the life and health of the crew. Space is an inhospitable place. A long-duration space voyage will come with (in order of danger to explorers and ability to palliate for): bone loss, muscle atrophy, loss of visual acuity, psychological issues that come with isolation,

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[128] Ibid.
[129] Zubrin, *Entering Space*, xii-xiv.

orthostatic intolerance, and radiation dangers. These challenges have been under study since human spaceflight first started, and mitigation techniques can reduce threats to acceptable levels.

Bone loss, muscle atrophy, cardiac issues, and orthostatic intolerance can be grouped under the same heading as they can be managed in much the same way. The primary technique of controlling these risks would be the application of artificial gravity in transit. Bone loss and muscle atrophy are related as they are both caused by the unloading of the musculoskeletal system when living in microgravity. However, the application of artificial gravity has been tested to a very limited amount in small centrifuges on orbit. The application of artificial gravity to an entire spaceship or a significant portion thereof would be preferred, and is theoretically feasible. If artificial gravity induction becomes a limiting factor for a space mission, there are alternative methods which may be applied. Standardized fitness routines using submaximal loads and the use of lower body negative pressure units to limit orthostatic maladjustment have been studied to great effect on Space Shuttle and ISS missions. There are also medications which could be ingested or injected to limit the effects of bone loss, particularly antiresorptive drugs which reduce bone loss in general and recombinant human parathyroid hormone which is used on Earth to stimulate bone formation. Crew selection must also play a factor. Crew members must have high pre-flight bone densities with no hereditary history of osteoporosis, as well as no history of kidney stone formation.[130]

Loss of visual acuity is a newer phenomenon in spaceflight which has had its onset among astronauts since the increase of mission duration for the ISS program. This loss is characterized by loss of near-sight visual acuity. While the exact source of this loss is still unclear, it is thought to be brought about by the cephalad fluid shift experienced in microgravity.

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[130] Jay Buckey, *Space Physiology* (New York: Oxford U. Press, 2006), 24-25.

As a practice, astronauts which fly to the ISS are issued a pair of adjustable spectacles for use when visual acuity loss begins.[131] There is a high probability that the induction of artificial gravity may have a mitigating effect on this risk, as fluid shift can be diverted in this way.

Perhaps the greatest risk to humans in transit from Earth to Mars is that of psychological distress. "…[I]nterpersonal conflict on a long-duration space mission has the potential to terminate missions and is arguably more of a risk to a mission than any other medical or physiological factor."[132] Interpersonal conflict is just one of many psychological issues which can have a detrimental effect on missions. Another major issue which has been recorded amongst cosmonauts is a malady called "asthenia." Asthenia is characterized by a loss of motivation, minor to major depression, weakness, rapid fatigue, irritability, and memory and attention deficits.[133] Finally, the severe isolation which accompanies long-duration spaceflight will bear its own toll on those who journey to Mars.

The primary ways to mitigate for psychological factors on a Mars mission would be crew selection criteria, team-building exercises during and after selection, a medical kit which includes basic psychological medications, and copious amounts of free time for the crew. Crew selection criteria would be the first line of defense for psychological problems in flight. First, any potential crew members that have a personal or family history of psychological problems would be selected out. Team building exercises should be conducted during training to determine optimal crew placement, avoiding interpersonal conflicts. During actual flight, interpersonal conflict will almost certainly become an issue. To prepaare for this, crews must be trained in relevant conflict resolution techniques during training with additional refresher training during

[131] Thomas H. Mader, et al., "Optic Disc Edema in an Astronaut After Repeat Long-Duration Space Flight." Journal of Neuro-Ophthalmology 33, no. 3 (2013): 249-55. doi:10.1097/wno.0b013e31829b41a6.
[132] Buckey, 35.
[133] Ibid, 38.

flight. Astronauts in transit will encounter large amounts or boredom and tedium. To compensate for this, astronauts must be given a job which is their sole responsibility, and ample amounts of free time which they would fill with activities of their own choosing. Personal electronics and computers should be provided which will be able to hold large amounts of music, book, videos, etc. for astronaut entertainment. Also, group activities, such as movies or sporting event viewing should be scheduled for the crew to boost morale. Finally, an onboard computer should be included during the mission that will allow medical personnel to accurately detect any problems at an early stage.[134]

Finally, radiation is often referred to as a "show-stopper" for any Martian mission. Radiation in space comes from three specific sources, only two of which are relevant to long-duration deep-space flight. The first is the sun. The sun produces solar particles of high radiation which stream forth constantly. During a coronal mass ejection (CME) more of these particles stream forth than normal. These particles consist mainly of protons, with the potential for ions being present. Currently, there is no reliable method by which to predict CMEs. Typically, these particles contain 1-100 MeV (mega-electron volts, a measure of energy). Normal spacecraft shielding such as that used aboard the ISS can prevent dosing of crewmembers by normal range (non-CME) particles. In the event of a CME, water can be used to augment normal shielding.[135]

The second relevant radiation type which the crew of a Mars mission will encounter is Galactic Cosmic Radiation (GCR) which originates in supernovae many light years away. The particles consist of protons and many are high-energy, high-atomic number particles, such as iron. These are called HZE particles. The danger in HZE particles is that the amount of shielding

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[134] Buckey, 46-49 and Gilles Clément, *Fundamentals of Space Medicine* (New York: Springer, 2011), 2nd ed., 217-52.
[135] Buckey, 53-73.

required to prevent dosing of crewmembers is massive, on the order of tens of meters of material compared to normal shielding which is typically on the order of millimeters thick. As such, there is no technology in existence which can mitigate for HZE. Even more dangerous is the fact that HZE are heavy and energetic enough to produce secondary radiation when they strike typical shielding materials, such as lead.[136]

There is a risk of radiation dosage in long-duration flights to Mars. How large of a risk? Zubrin labels the radiation risk a “dragon” by which humanity could frighten itself out of trying to go Mars.[137] Studies have shown that a prompt dose of 75 rems of radiation would result in little to no health effect on a person. For a two-and-a-half-year voyage to Mars, the crew would receive approximately 50 rem total. While not a small dose by any means, this is certainly within the limits of human safety. In fact, for a chronic radiation dose of 100 rems, a person could expect a 1.8% higher chance of being diagnosed with terminal cancer in their lifetime. If this were the show-stopper risk, most astronauts would take that risk for the glory of being the first person on Mars. Moreover, recent simulations suggest that GCR does not pose a major health dilemma for crewmembers journeying to Mars.[138]

Funding

A mission to Mars does not have to be prohibitively expensive. While NASA’s current plan has been valued at $80 to $100 billion over a 20-year timeframe, The Mars Society, an advocacy group, has gone on record saying that humans could be sent to Mars for as little as $30 billion

[136] Ibid.
[137] Zubrin, *Case for Mars*, 126-33.
[138] V. A. Sakovich and V. F. Semenov, "Radiation danger in manned flight to Mars. Concept," *Atomic Energy* 99, no. 4 (October 2005): 740-746, doi: 10.1007/s10512-006-0010-y.

and in 10 years.[139] While values range wildly between Mars missions, the question remains, "How much will it cost?" The truth is that all of the hardware needed for a humans-to-Mars mission has existed since the 1990's. Since that time, the cost of launch has fallen, meaning that the trip could be done for less than would have been anticipated 20 years ago.

The question of money, how much and from where, will continue to dominate the debate until after the first humans have set foot on the Red Planet. As of 2017, only governments have the type of resources needed to launch an all-out exploration campaign. However, with private organizations beginning to blossom in the space industry, a time could come when space flight activities, including interplanetary travel, may become the realm of private business.

Sustainability

Finally, any exploration efforts to Mars should be part of a sustainable program. Simply putting a person on the surface, taking some pictures, and then returning them to Earth would not be worth the effort or the cost. A Mars mission plan needs to be sustainable and have a purpose of leading to greater missions and eventual colonization. Sustainability includes three factors: affordability, continuing presence, and the ability of the "Mars base" to produce for its own needs. While there are several obstacles to sustainability, these are being addressed by scientists around the world. Companies are working toward driving down the cost of launch to LEO which, in turn, will drive down the cost of launch to Mars. There are "Mars farming" analogs testing the ability of crew to grow their own food in Martian regolith. There have been, and will be, missions concerning the presence of water on the Martian surface and how to access and utilize this resource. With the work being conducted now moving toward a more sustainable

[139] "Mars or bust: The who, why and how of a manned mission," *The Economist*, accessed April 29, 2017, http://thefutureishere.economist.com/article-marsmission-transportation.html.

Martian mission, it is only a matter of time before a Mars mission could be fully capable of sustaining itself on the surface indefinitely.

First, it is becoming less expensive to launch into LEO. This is due to work on reusability by firms such as SpaceX. SpaceX was founded on the simple principle that lowering the cost of launch would make exploration more sustainable. In this effort, they have made great strides. SpaceX's rockets are completely new designs. This allows them to streamline the construction process and be innovative with new manufacturing techniques, such as stir-welding.[140] Additionally, they compete with other launch firms based on cost.[141] A Falcon 9 rocket costs approximately $62 million, which means a cost of $2,719 per kg to LEO.[142] The closest comparison to the Falcon 9, the Atlas V, cost estimates are approximately $164 million per launch. However, $64 million of that estimate is comprised of annual pad maintenance fees, which United Launch Alliance (ULA) pays in advance.[143] This could be compared to the Space Shuttle, which had less payload capacity and cost about $450 million per launch.[144] Finally, SpaceX is working at total reusability of their rockets. Currently, SpaceX has successfully landed nine of fourteen first stage attempts.[145] They also are working on second stage landings, but have

[140] Chris Anderson, "Elon Musk's mission to Mars," *Wired*, October 21, 2012, accessed April 29, 2017, https://www.wired.com/2012/10/ff-elon-musk-qa/.
[141] Ibid.
[142] "Capabilities and services," SpaceX, accessed April 29, 2017, http://www.spacex.com/about/capabilities.
[143] Colin Clark, "ULA fires back at SpaceX at Space Symposium; details launch costs," *Breaking Defense*, May 20, 2014, accessed April 29, 2017, http://breakingdefense.com/2014/05/ula-fires-back-at-spacex-at-space-symposium-details-launch-costs/.
[144] "Space Shuttle and International Space Station," NASA/Kennedy Space Center, accessed April 29, 2017, https://www.nasa.gov/centers/kennedy/about/information/shuttle_faq.html#10.
[145] Sean O'Kane, "Watch a GIF of every successful — and failed — SpaceX Falcon 9 landing attempt," *The Verge*, April 10, 2017, accessed April 29, 2017, http://www.theverge.com/tldr/2017/3/30/15132014/spacex-rocket-landing-attempt-history-watch-videos-explosions.

yet to attempt one. The first reused first stage was successfully launched on March 30, 2017, and landed on the autonomous drone ship, *Of Course I Still Love You*.[146]

Second, any Mars program should continue past the initial landing. If the entire thrust of the mission is to place a human on Mars and then bring them home, never to return, then the entire program is flawed. There would be no gain beyond the basic science that could be conducted in one or two crewed missions. For real payout, the first mission must be only a small part of a greater effort which could potentially lead to colonization. The establishing of a colony on Mars would fulfil the need for humanity to maintain a separate presence away from Earth in the case of an inevitable cataclysmic asteroid strike. Carl Sagan was famous for saying that Earth lies within a "cosmic shooting gallery." Asteroid strikes are not common, but they do happen with some frequency that is generally based on size. A small meteorite or asteroid roughly 4m in size and having an explosive yield of roughly 16 megatons can be expected to hit the Earth once every year. Whereas, an asteroid the size of that which killed off the dinosaurs (roughly 10km in diameter), and having a yield of 240 billion megatons can be expected to collide with Earth every 60 million years.[147] Moreover, by having a base of operations on Mars, humanity would then be closer to deep space heavy industry and mining within the Main Belt of asteroids itself, which is an extremely lucrative prospect.[148]

Finally, a sustainable Mars base will need to produce its own food and water. On Earth, there are microbes and bacteria in soil which allow plants to grow. On Mars, no such microbes are known to exist. There are at least two ways to approach this situation. First, a crew could use

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[146] Darrell Etherington, "SpaceX's first Falcon Heavy launch could attempt upper-stage recovery," *Tech Crunch*, March 31, 2017, accessed April 29, 2017, https://techcrunch.com/2017/03/31/spacexs-first-falcon-heavy-launch-could-attempt-upper-stage-recovery/.
[147] Zubrin, *Entering Space*, 130-32.
[148] "Asteroids will unlock the solar system's economy," Planetary Resources, accessed May 26, 2017, http://www.planetaryresources.com/asteroids/#asteroids-market-opportunity.

aeroponics to grow food without soil. This is a process used on Earth extensively, but it is expensive, requires running water constantly, and minerals must be added to the water. The second option is to use analogs on Earth to develop techniques to grow plants in Martian soil. In a study conducted at Florida Technical Institute, plants were grown in a Martian regolith simulant from Hawaii, a simulant that was enhanced with nutrients, and in potting soil. It was found that the plants grown in both simulants were less hardy and required slightly more germination time.[149] Other international studies have shown that growing plants in Martian regolith analogs requires the addition of biologics from Earth.[150] However, this does make progress toward proving that a Mars base could become fully self-sustaining when astronauts arrive.

Previous Mars orbiters and landers have shown that water ice exists on the planet near the poles. *Mars Reconnaissance Orbiter* also discovered the existence of perchlorate near the Martian equatorial region. Additionally, NASA has been successfully testing water reclamation techniques on ISS. The existence of water on Mars has been a long-debated subject. From orbit, Mars seems dry and lifeless. However, upon closer inspection with landers, there is abundant evidence that water existed in liquid form on Mars, albeit a very long time ago. What happened to that water is still very much a mystery. What is known is that water ice exists at higher latitudes and underground.[151] When this ice melts, it evaporates into water vapor because Mars lacks the atmospheric pressure for liquid water to exist.[152] However, in studies conducted

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[149] Anna Heiney, “Farming in ‘Martian gardens,’” NASA, September 28, 2016, accessed April 29, 2017, https://www.nasa.gov/feature/farming-in-martian-gardens.
[150] Rachel Feltman, “Scientists just grew vegetables in 'Martian' soil -- but there's a catch,” *The Washington Post*, 2016, https://search-proquest-com.ezproxy2.apus.edu/docview/1771671763.
[151] Andrea Thompson, “Water ice on Mars confirmed,” *Space.com*, July 31, 2008, accessed April 29, 2017, http://www.space.com/5686-water-ice-mars-confirmed.html.
[152] C. S. Hvidberg and H. J. Zwally, “Sublimation of water from the north polar cap on Mars,” (paper presented at the Mars atmosphere modelling and observations workshop held at Grenada, Spain, January 13-15, 2003), accessed April 29, 2017, http://www-mars.lmd.jussieu.fr/granada2003/abstract/hvidberg.pdf.

through the 2010's, NASA scientists have discovered evidence of perchlorate saline liquid on the surface. These findings were highlighted in 2015 when NASA announced that an observed phenomenon called "recurring slope lineae" was caused by magnesium perchlorate and sodium perchlorate running down slopes in the Vallis Marineris region of Mars during warmer periods.[153]

Water is the basis of all life that has been observed. It is also one of the most important and heavy resources astronauts will need during a Mars mission. The ability to produce or procure water on Mars is the key to sustainability of a Martian mission architecture. Even if it is difficult to find water on Mars, with new technologies, actual water does not need be sent across the distance. The Sabatier reaction, as previously discussed, could be used by sending a small amount of hydrogen along with the astronauts. This would have a double benefit as the reaction could also provide fuel for surface craft. Combined with water reclamation techniques already in use, water should not prove to be a difficult challenge to manage.

Discussion

With the criteria of crewmember health, funding, and sustainability being selected, the next step will be to prioritize the criteria and grade each mission model on a pass or fail scale. Whether a model passes or fails on each criterion is based on whether or not the model broaches the subject, how the criteria is planned for, and the feasibility of those plans.

Crewmember health will always be of the utmost importance. The selection criteria for crewmember health is graded on what type of orbital trajectory the mission will take, length of time in space, and any built-in mitigating factors which the architecture addresses. Funding will be analyzed considering costs for the mission as estimated by the mission architect or industry

[153] Mcewen, et al., "Recurring slope lineae."

experts. Sustainability will consider both the financial feasibility and the planned continued operation of humans on the Martian surface. Crewmember health criteria for selection of a Martian mission is a balancing act between acceptable and unacceptable risks. NASA's motto in launching astronauts is to launch with the lowest acceptable risk. Some might claim that NASA has not always followed this ideology, as they have had three well-documented space disasters: *Apollo 1*, *Challenger* (STS-51-L), and *Columbia* (STS-107). Even so, NASA has been known to put crewmember health above all other considerations when planning crewed missions.[154]

Funding for Mars missions is the second most important factor, particularly since Mars missions will be among the most expensive human endeavors ever embarked upon. While each program would have different funding requirements, most would be publicly funded, meaning that nations or public-private partnerships would bear the cost of the mission. Funding is also a strong indicator of mission feasibility. A well-funded mission has a greater chance of success than a similar mission funded at a lower level.

Sustainability is the third deciding factor for any Mars mission. Not only should humans go to Mars, they should begin to make a permanent home there. In this respect, not all missions are created equal. Some missions call for a single landing, some call for multiple landings, and still others call for complete colonization. The choice for which mission to pursue may hinge on how the future looks from the Martian surface.

[154] "Crewmember health is a top priority," NASA, March 3, 2015, accessed May 15, 2017, https://www.nasa.gov/feature/crewmember-health-is-a-top-priority.

Das Marsprojekt

Crewmember Health

Das Marsprojekt does not consider these threats to human safety except for a single sentence about radiation in the preface to the 1962 edition of the work[155], it does, however, mention that the plan would use a Hohmann transfer orbit, which is the slowest, most fuel-effective way to travel to and from Mars. The trip would take 260 days outbound.[156] Using the BEIR report on radiation,[157] as well as Zubrin's work on radiation amounts on Mars missions, a total amount of estimated rem for any mission can be attained by finding the total time spent in space, in days, and dividing by 365, then adding in total amount of time on Mars. For *Das Marsprojekt*, the estimated rem would be 78. This is lower than the 100 rem dose the BEIR report is based off of, but higher than both conjunction and opposition class missions as described in Zubrin.[158] In determining the pass or fail grading for *Das Marsprojekt* pertaining to crewmember health, von Braun's plan fails due to extended microgravity exposure with no mitigation and little to no radiation shielding.

Financial Feasibility

Dr. von Braun's mission architecture immediately fails the funding and feasibility test due to the large nature of the program. In requiring 46 reusable shuttle orbiters rated at 25 tonnes to LEO, the funding for this project has already grown to immense proportions. The American

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155 Von Braun, xviii
156 Ibid, 61.
157 *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2* (Washington D.C.: National Academies Press, 2006.
158 Zubrin, *Case for Mars*, 129-31.

Space Shuttle program orbiters were rated at 24 tonnes to LEO.[159] Each orbiter cost approximately $2 billion in the years they were commissioned. It has been estimated that they cost approximately $450 million per launch.[160] The cost per launch takes into account the cost of running the program over a full year divided by the number of launches in a single year. If the amount of operations costs for year 1993 was $629.7 million[161], the cost of the operation of the von Braun orbiters can be deduced by dividing the operational costs for the program by the number of flights. As his plan called for 950 launches over an eight-month period, the operational cost of each launch is $660,000. However, this oversimplifies the situation, as shuttle per launch costs were passed on to payload operators at a cost of $44 million per mission, called the "marginal cost per flight."[162] This estimate is the savings to NASA at the cancellation of a single flight of the Shuttle. If this estimate is used, the cost of operations for the von Braun fleet would be roughly $41.8 billion. The construction cost of the fleet can be based on the similar Shuttle orbiters, which would total $92 billion. So the cost of the construction of the von Braun Mars ships would start at $93 to $133 billion, which does not include development or real costs for the actual Mars ships themselves. As can be seen, this program would become unwieldy in short fashion and is not feasible.

Sustainability

Dr. von Braun's plan calls for a single mission to the Red Planet. Though this mission would be of an extended length, it would still be only aa single mission. Furthermore, there is no

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[159] "Shuttle technical facts," ESA, accessed May 16, 2017, http://www.esa.int/Our_Activities/Human_Spaceflight/Space_Shuttle/Shuttle_technical_facts.
[160] Government Accountability Office, *Space transportation: The Content and uses of shuttle cost estimates* (Washington D.C.: GAO, 1993), pdf, accessed May 16, 2017, http://www.gao.gov/assets/220/217465.pdf.
[161] Ibid, 5.
[162] Ibid, 8.

discussion for what would happen to the associated hardware after the completion of the mission. If the infrastructure and hardware are single use, then the mission is a one-off and should not be attempted because the cost would not be worth the journey. As for sustainability, *Das Marsprojekt* is graded as failing.

Mars Direct

Crewmember Health

Zubrin's *Mars Direct* plan considers crewmember health extensively. He addresses radiation health, microgravity mitigation, and psychologic health. For radiation health, he contends that the amount of radiation received during a voyage to Mars would be roughly 50 rem for a round trip to Mars.[163] This is roughly enough radiation to cause a 1% increase in the incidence of fatal cancers for the astronauts over a thirty-year span.[164] Concerning microgravity mitigation, Zubrin proposes using the burnt out final stage of a rocket on a tether rotating around the spacecraft. If done correctly, this would theoretically be able to induce artificial gravity on the spaceship. The relevant equation is:[165]

$$F = (0.0011)W^2R$$

Where F is the gravitational force induced in Earth gravities, W is the number or rotations per minute (rpm), and R is the length of the spin arm in meters.[166] This equation can be manipulated in several ways to achieve the desired results. For a trip to Mars, it would most likely be desirable to induce Martian gravity (F = 0.38). In that case, for a rotation of 1 rpm (W = 1), R would become 345 m. This amount of rotation should prove optimal for a long-term mission to

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[163] Ibid, 132.
[164] Ibid, 128-29.
[165] Ibid, 135
[166] Ibid.

Mars. If a shorter spin arm is desired, it can be achieved with higher rpms. NASA studies have shown that astronauts can only handle up to 6 rpm reliably, which would give a spin arm of 10m. However, a crew member in a spaceship spinning at 6 rpm with an arm of 10m would experience significantly less gravity at the level of their head as opposed to their feet, which would be extremely disorienting at first. This alone is not a reason to negate the 6-rpm spin rate but, when coupled with the Coriolis effect that would happen when moving about, may lead to more disorientation than necessary. With a longer spin arm and slower rpm, these effects can be negated to being insignificant.[167]

NASA scientists have concluded that this application would simply not work on a ship the size of Zubrin's HAB.[168] However, they may not be considering that Zubrin has his crew tethered to the burnt out final stage as a counter-balance, which would make this more approachable. Another detractor from artificial gravity is that solar arrays and antenna that need to be oriented correctly would be spinning along with the spacecraft. Again, Zubrin refutes this by pointing out that technology now exists that could keep solar arrays pointed at the sun if the spin plane is pointed at the sun. An omnidirectional antenna can be used as opposed to a pointed array.[169] This would have the entire assembly floating through space like a cartwheel, but would go a long way toward eliminating some of the more troubling health effects that spaceflight brings.

Considering psychology, Zubrin points to the many years of unofficial testing via war and service in which humans have endured psychological hardships greater than those which a Mars crew will face. A submarine crew in the 21st century is a small group (up to 150) placed in

[167] Zubrin, *Case for Mars*, 135-138.
[168] Rachel Feltman, "Why don't we have artificial gravity?" *Popular Mechanics*, May 2, 2013, accessed April 29, 2017, http://www.popularmechanics.com/space/rockets/a8965/why-dont-we-have-artificial-gravity-15425569/.
[169] Zubrin, *Case for Mars*, 138.

a potentially deadly environment and close quarters for up to 9 months at a time. This is an excellent analog to a Mars mission. His contention is that the human link in the "chain to Mars" will perhaps be the strongest one, as humans are able to adapt and overcome.[170]

When it comes to crewmember health, Zubrin's plan successfully plans for most of the big health concerns which crews will deal with en route to Mars. For that, his plan receives a passing grade.

Financial Feasibility

Zubrin's plan is considered one of the least expensive in many aspects. He states that a work-group study of a similar "Mars Semi-direct" plan found that the cost of the mission for three crews to Mars would be about $55 billion.[171] This is less than NASA's current plan and encompasses a more robust system than anything they have planned vis-a-vis Mars. However, this plan was priced using the cost of the Ares (now SLS) rocket. The plan would need nine launches, three per launch window. With SLS launch costs being between $600 million and $1 billion and the cost of a comparable Falcon Heavy launch being $150 million,[172] the total cost of the plan can be reduced by another $5-10 billion, as launch and operational costs would be less with the SpaceX launchers. With consideration, Mars Direct receives a pass grade as being the one of least expensive plans if funded by a government.

Sustainability

Zubrin's plan calls for the creation of a network of landing sites which would lead to further colonization in the future. With the need for two launches every year, the cost is well

[170] Ibid, 138-41.
[171] Zubrin, *Case for Mars*, 80-81.
[172] Dale Skran, "Battle of the Colossi: SLS vs Falcon Heavy," *The Space Review*, April 27, 2015, accessed April 29, 2017, http://www.thespacereview.com/article/2737/1.

within sustainability standards. Furthermore, Zubrin's plan relies extensively on ISRU, which is key to a self-sustaining Martian base or colony. Finally, Zubrin sees Mars only as a stepping stone in the path to humanity's grasp of the solar system. As such, it would become an important way-station on the journey to the outer solar system. Therefore, Mars Direct receives a passing grade for sustainability.

Aldrin's Mission to Mars

Crewmember Health

Aldrin's *Mission to Mars* plan takes crewmember health into consideration in some respects, but remains silent on others. His biggest recommendations are the use of the ISS to study the long-term effect of microgravity on the human body, the use of cycler orbits to allow an astronaut the ability to take a 5-month journey to Mars and an 8-month journey back, and an incremental approach to a human mission.

The use of the ISS as a testbed for new technologies has been ongoing since it was "completed" in 2011. Medical testing of astronauts has been ongoing since Yuri Gagarin traveled to space in 1958. However, the deep space environment is a novel one for space travelers. The furthest a human being has flown away from the earth is about 384,400 km (average), the distance between the earth and the moon. The distance to Mars vacillates between 54.6 million km and 401 million km, with an average of 225 million km. There is no current analog to the deep space environment. While the ISS provides an excellent testbed for long-term microgravity exposure, it does not fully encompass the deep space testing which NASA would like to accomplish before humans are sent to Mars. Therefore, the ISS is more analogous to a Mars mission in respect to human health, but has proven quite useful in building a bridge between different cultures and peoples.

Aldrin's cycler orbits, while quite useful for moving cargo to Mars, would require a significant infrastructure to be fully developed to the point where a 5-month journey to Mars and an 8-month return journey is achievable. In the meantime, the first ship built and sent on the Aldrin cycler would have a 5-month outbound time and a 10-month return time. This would put the crew's total time in space at 15 months, where they would receive an estimated 79.5 rem in transit. While this is still below the BEIR scale standard, it is higher than other proposed plans. One of the hallmarks of Aldrin's plan is the incremental approach he supports in going to Mars. By returning to the moon, then flying to an asteroid, then going to Phobos, then landing on Mars, his plan builds upon previous experiences at each step. While some of these steps may be analogous (landing on an asteroid or Phobos is very different than landing on Mars), it would allow for ample research into the deep space environment and its effects on human life.

Aldrin's plan, while it attempts to mitigate for many dangers, fails to provide new ideas to better protect astronauts from the dangers of the journey. However, it still provides multiple learning opportunities along the path which will allow for greater protections in the future. For this, Aldrin's plan passes the crewmember health standard.

Financial Feasibility

Aldrin's plan calls for the use of the SLS system to build a large interplanetary cruiser, or cycler, on orbit. This plan would also call for a way-station to be constructed in Earth orbit and in Martian orbit. With so many pieces, this plan has many opportunities for major cost overruns. Under current funding and administrations, this plan lacks feasibility, but may become more feasible in the future when NASA turns from the ISS and begins to build an infrastructure for travel to Mars. With so many moving parts and large ships, this plan fails on the funding test, as it is beyond the current ability of any national government space agency. If, in the future, funding to NASA or Roscosmos were to be increased substantially, this plan would have much better chance of being a feasible option.

Sustainability

Buzz Aldrin's plan is really a framework for what he sees as the future of spaceflight. The cycler system is a key component to Aldrin's plan, and if fully realized would make the cost of sending people and supplies to Mars significantly less over many years. His incremental approach also adds to sustainability as it would give humanity access to asteroids as a result. Mission to Mars is given a passing grade in sustainability.

NASA's Journey to Mars

Crewmember Health

As stated earlier, NASA hold crewmember health to the highest standard. As such, their plan is built around developing the least risky architecture possible. They are currently using the ISS as a testbed to human health in space and they are developing new technologies, such as semi closed-loop life support systems and oxygen generators, for a Mars mission.

NASA's biggest advantage in this area is their level of expertise in astronaut health. They have years of experience with crewed flight. However, their experience declines rapidly when travelling beyond the moon. NASA, given their history of fatal accidents, has become extremely risk averse.[173] As such, they have focused on mitigation strategies such as shielding and

[173] Marc Boucher, "Space is Dangerous - Be Prepared," Space Ref, August 8, 2014, accessed May 15, 2017, http://spaceref.com/astronauts-2/space-is-dangerous---be-prepared.html.

pharmaceuticals. As of the last update on the potential of the first SLS mission (EM1) being crewed, NASA had decided against sending humans into an orbit beyond the moon on their first attempt.

Pertaining to new technologies, NASA has moved toward an eventual Mars mission. Primary among these moves are the closed-loop water retrieval system currently in use aboard the ISS and the MOXIE test unit which will be sent to Mars on the Mars 2020 rover. The Water Recovery System aboard the ISS processes wastewater and astronaut urine as well as water vapor into fresh potable water. This system allows less payload space to be used by carrying water to orbit.[174] While this does not completely close the life-support loop of spacecraft, it goes a long way toward making extended missions sustainable from a human need perspective. The MOXIE system uses a process called solid oxide electrolysis to strip single atoms of oxygen (atomic oxygen) from the carbon dioxide in the Martian atmosphere and joining them to other atomic oxygen atoms to create breathable pure oxygen and carbon monoxide, CO, which can be used as fuel or further processed into methane with the addition of hydrogen.[175]

NASA's expertise as well as their leverage of new technologies lands them firmly within the passing grade file. However, a word of caution should be issued in response to risk aversion. While mitigating for some risks is prudent, spaceflight is still inherently dangerous. As such, risk aversion can lead to major delays and eventual cancellation of projects if not kept in check.

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[174] D. Layne Carter, *Status of the Regenerative ECLSS Water Recovery System* (Huntsville, AL: NASA, 2009), pdf, accessed May 16, 2017, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090033097.pdf.
[175] "Mars OXygen ISRU Experiment Project," *NASA TechPort*, accessed May 16, 2017, https://techport.nasa.gov/view/33080.

Financial Feasibility

NASA's proposed plan calls for the use of SLS. That is about the extent of their planning, as JtM is a capability driven model. However, the NASA inspector general recently stated that the cost of JtM will run to "$400 billion by the time a second visit to the Martian surface is completed in the 2040s."[176] While this is still within the NASA budget, the cost overruns associated with this program will most likely be taken from other vital programs within NASA, such as planetary sciences and research. While JtM is seen as passing the funding test based on current cost and budget estimates, the recommendations of the Inspector General should be taken under consideration by the incoming NASA administration to lower operating costs and leveraging what technology already exists to their advantage. Some of these recommendations include: international partnerships, public-private partnerships, full scheduling of all planned mission, and using cost analyses when conducting feasibility studies for future JtM plans.[177]

Sustainability

NASA has been developing capabilities regarding sustainability on the Martian surface and ISRU. However, as per the Inspector General's report, JtM is not sustainable after the 2040's at current budget levels. As such, JtM may have a very good chance at being an Apollo-style "boots on the ground" mission with no foreseeable follow on. Therefore, Journey to Mars is given a failing grade for sustainability.

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[176] NASA Office of the Inspector General, *NASA's Plans for Human Exploration Beyond Low Earth Orbit* (Washington, D.C.: NASA, 2017), 39.
[177] Ibid, 40.

Mars Base Camp

Crewmember Health

The Mars Base Camp model is based on the architecture that will be in place once SLS and *Orion* are fully functional. As such, there is little mentioned in this model about crewmember health. However, a look at some of the details of the mission point to the ability to surround parts of the craft with fuel cells which can significantly reduce the amount of radiation received by the crew. In figure 6, the fuel cells are shielded in gold foil and surround the two *Orion* capsules. As Mars Base Camp shows the use of some mitigation techniques, it is given a grade of passing in the area of crewmember health.

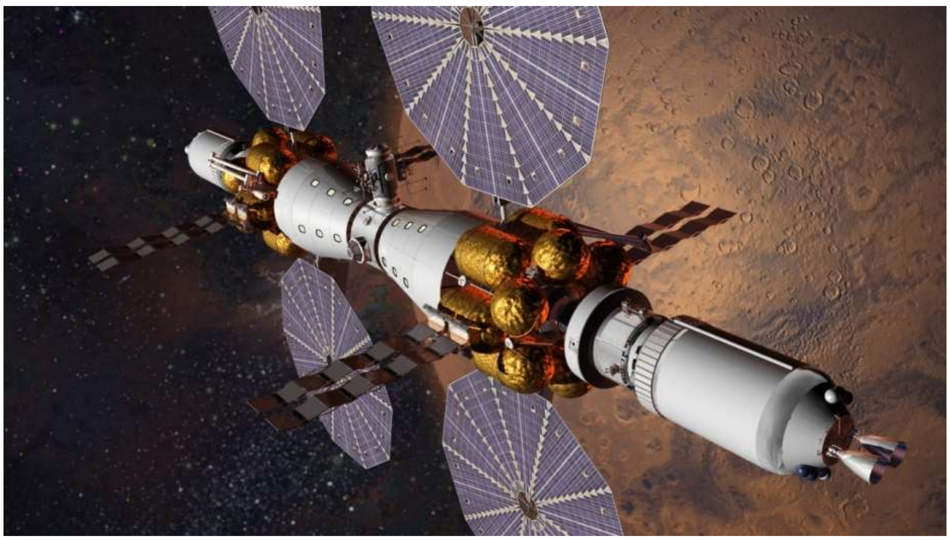

Figure 6: Artist's rendition of the Mars Base Camp Concept. Source: Lockheed Martin, http://www.lockheedmartin.com/us/ssc/mars-orion.html.

Financial Feasibility

Lockheed Martin's MBC study uses the existing *Orion* infrastructure and technology to fly a mission to Mars using a space station. The costs associated with MBC would be for two *Orion* capsules, the habitation capsules, and at least five SLS launches. Operational costs for such a mission have yet to be determined. However, it would be realistic to see the costs of this mission run from $10 billion to $20 billion, based on past NASA performance. While this mission does not put humans on Mars, it is an excellent precursor which leverages NASA's existing equipment. For that, MBC receives a passing grade in funding.

Sustainability

MBC is designed as a one-off mission to Martian orbit. Though it is an excellent precursor mission, it will not be graded on sustainability, as it does not put humans on Mars.

The Martian

Crewmember Health

Andy Weir's work is based on current planning studies into a crewed mission to Mars program. While fantastical in how some health concerns are addressed (entire *Hermes* spaceship rotating around a non-rotating center section to accomplish artificial gravity), his work shows promise in that many crewmember health concerns are allayed by systems onboard. Weir does not mention any radiation mitigation techniques in the book and the crew of the *Hermes* extends their time in space without regard to their wellbeing. As per *The Martian*, the crew of the Hermes spent a minimum of 1077 days in space: 124 days of outbound travel, 30 days' surface stay, 390 days of inbound travel, and 533 days of mission extension. This total is far beyond any amount of time ever spent in space by a human being at one time. As a response to questions about this subject, Weir stated that the crew of the *Hermes* had a "[…] really thin, light, flexible material that blocks all radiation. There's nothing even remotely like that in the real world. That was the magic I gave him so the story would progress. Otherwise Mark would have different kinds of cancer."[178] As one of the most major crewmember health considerations is essentially side-stepped by *The Martian*, it earns a failing grade on the subject.

Financial Feasibility

In *The Martian*, *Hermes* is described as a massive ship. Using only visuals from the movies and a description from the book, only a rough estimate can be made as to how much such a mission would cost. It is described as the "most expensive thing ever built."[179] As such, *Hermes*, as depicted in the film, is very spacious and uses a large nuclear reactor to power its ion engines. Assuming minimal launch mass on these pieces, the entire ship as seen in the film would take 50 launches. As described in the book, the project took over 10 years and the cooperation of every major space agency in the world with the exception of the Chinese agency.[180] The pre-supply for each Ares mission in the book took 14 launches.[181] While *The Martian* is an enjoyable read, from a funding aspect, the program in unrealistic. Therefore, *The Martian* receives a failing grade on funding.

Sustainability

Andy Weir's mission architecture is designed around reusing the *Hermes* interplanetary craft for five or six missions to Mars.[182] There is no discussion about follow-on missions after the *Ares 5* mission. With such a large investment in infrastructure, it would be prudent to get the most use out of the investment. However, as there is substantial international cooperation in *The*

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[178] Andy Weir quoted in Clara Moskowitz, "'Martian' astronaut would get cancer if mission were real, author says," *Scientific American*, October 3, 2015, accessed May 16, 2017, https://www.scientificamerican.com/article/martian-astronaut-would-get-cancer-if-mission-were-real-author-says1/.
[179] Weir, *The Martian*, 203.
[180] Weir, *The Martian*.
[181] Ibid, 50.
[182] Weir, *The Martian*, 50.

Martian there would most likely be continued investment into the technologies needed to travel to Mars. Therefore, *The Martian* receives a passing grade for sustainability.

Mars One

Crewmember Health

The Mars One plan is built around not having a return infrastructure in place. As such, crewmember health seems to be neglected by the company. Crewmember health is mentioned in the "Risks and Challenges" section of their website, but is not readily seen elsewhere. Mars One has contracted a study into Environmental Control and Life Support System (ELCSS) technologies, which was conducted by Paragon Space Development Corporation.[183] This study shows that there are significant challenges to developing ELCSS for use on Mars and that such a system would require a generous amount of repair parts after a design two-year period in which maintenance would not be required. Such a system has never been developed or tested. As Mars One only minimally accounts for crewmember health in their documentation, they receive a fail grade in that regard.

Financial Feasibility

Mars One's plan is touted to be the least expensive at roughly $6 billion. However, it is unlikely that Mars One would be able to acquire even that "small" sum of capital using their existing funding models. The initial Mars One plan of funding the mission using television and advertising rights, as previously discussed, would not produce enough capital to fund the

[183] Gary Finger, Gary Lantz, and Tad Theno, *Mars One Habitat ECLSS (ECLSS) Conceptual Design Assessment* (Tuscon, AZ: Paragon SDC, 2015), pdf, accessed May 16, 2017, http://www.mars-one.com/images/uploads/Mars_One_Habitat_ECLSS_Conceptual_Design_Assessment.pdf.

mission. Without government funding or sponsorship to bolster their plans, there is very little hope for success. As a result, Mars One's plan receives a failing grade.

Sustainability

Mars One's plan is to send crews to Mars for permanent relocation. They have conducted some studies into the requirements of such an enterprise, however, without an effective funding model in place, they will not even begin on their journey. If their plans do come to fruition, they plan on building a base on Mars that can be expanded as more settlers arrive. This is enough to give Mars One a passing grade on sustainability.

SpaceX

Crewmember Health

Elon Musk's vision for Martian colonization makes little mention of crewmember health. While Musk refers to the time spent en route to Mars as "fun," he brushes off the question of radiation shielding with a simple, "There's going to be some risk of radiation, but it's not deadly. There will be some slightly increased risk of cancer, but I think it's relatively minor."[184] He even mentions that in the case of a radiation event, such as a solar flare, the colonists could gather under some construct of water or reorient the ship to better protect the travelers. Experts agree with Musk that radiation is not a "show-stopper" for a Mars trip, but still feel that he glazed over the subject.[185] As for microgravity mitigation techniques, Musk makes no mention. As such, SpaceX's plan receives a failing grade in crewmember health.

[184] Elon Musk, "Making humans."
[185] Loren Grush, "The biggest lingering questions about SpaceX's Mars colonization plans," *The Verge*, September 28, 2016, accessed May 16, 2017, https://www.theverge.com/2016/9/28/13087110/spacex-elon-musk-mars-plan-habitat-radiation-funding-questions.

Financial Feasibility

Musk's vision for Martian colonization requires new "super-heavy" lifters and on orbit construction and fueling. The costs of developing these new technologies have not been publicized, but they are sure to be less than the same system being designed by NASA. Musk predicts the cost of constructing the Mars infrastructure to be roughly $560 million for a single Mars mission. This would be in addition to the operational costs of the mission which he estimates at $62 million.[186] While these numbers are very optimistic, they are much lower than any other mission that has been proposed. They will most likely rise as the mission comes closer to being a reality. SpaceX is currently running all their revenue streams at the highest levels to make this plan a reality. Therefore, SpaceX gets a passing grade for funding.

Sustainability

Elon Musk's vision calls for the colonization of Mars. It goes beyond Mars to see humans visiting Europa and Enceladus. Even though Musk's plans do not mention where settlers will live or work, he calls for sending a hundred settlers on each transport ship, a plan that would necessarily call for sustainability. He also delineates how propellant would be made *in situ* on Mars, which is a key to sustainability. As such, he is given a pass in that area.

[186] Musk, "Making humans."

Summary of Findings

The final pass/fail grading for crewmember health, funding, and sustainability is as follows:

Table 1: Pass/fail grading for crewmember health, financial feasibility and sustainability of Mars missions.

Mission	Crewmember Health	Financial Feasibility	Sustainability
Das Marsprojekt	fail	fail	fail
Mars Direct	pass	pass	pass
Aldrin	pass	fail	pass
Journey to Mars	pass	pass	fail
Mars Base Camp	pass	pass	n/a
The Martian	fail	fail	pass
Mars One	fail	fail	pass
SpaceX	fail	pass	pass

Using the criteria of crewmember health, funding, and sustainability a clear choice is evident as to which plan is most likely to succeed. Zubrin's *Mars Direct* plan holds the most potential, as it actively mitigates most of the obstacles in the way to Mars travel without over-relying on new technologies. It also is decidedly less expensive than any other humans-to-Mars mission plans to date. Finally, *Mars Direct* also follows a logical sequence of launches to promote sustainability of the mission to the point of colonization.

While Zubrin's plan hold the most promise and potential, the plan best situated to become a reality and bring humans to Mars is the SpaceX Mars Colonization plan. While it does require new technologies and multiple launches per spacecraft to fuel, the sheer audacity of SpaceX to not only make the plan but to start the plan on its way using their own funds could very much prove to be the deciding factor. While Mars Direct would be less expensive, SpaceX does have a funding plan in place and can make large investments into technology and spacecraft development. However, Elon Musk has stated that the timeline for such a mission is "intentionally fuzzy."[187]

I recommend a hybrid plan which uses current technologies (Falcon 9/Heavy, Crew Dragon) to begin human exploration of Mars in the short-term (5 to 10 years), while also conducting development of large colonial ships for long term colonization. As a precursor to this plan, they could partner with Lockheed to make Mars Base Camp a reality, using proximity to the planet to effectively operate remote landers and find areas which would be used for colony development. If SpaceX were to adopt such a plan and partner with NASA in a public-private partnership, Mars could be less than a decade away.

As for how such a plan should be funded, I believe that perhaps the time has come to give private industry a goal in sending humans to Mars. Charles Lindbergh completed the first solo-nonstop crossing of the Atlantic in 1927 to win the Orteig Prize, a $25,000 award for the first person to complete the feat.[188] The Ansari X Prize was awarded to Burt Rutan and Mojave Aerospace Ventures for sending a fully reusable spaceship on a sub-orbital flight twice in two weeks.[189] Even though the Ansari X Prize was $10 million, over $100 million was spent in development by the competing teams.[190] These types of prizes are a catalyst for new technologies and outside-the-box thinking and that power can be applied to Mars through a similar prize system. Zubrin has conceptualized such a prize: The Carl Sagan Mars Prize.

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[187] Musk, "Making humans."
[188] "Raymond Orteig – a $25,000 prize," Charles Lindbergh: An American aviator, accessed May 15, 2017, http://www.charleslindbergh.com/plane/orteig.asp.
[189] "Mojave Aerospace Ventures wins prize that started it all," Ansari Xprize, accessed May 15, 2017, http://ansari.xprize.org/teams.
[190] Ibid.

The Carl Sagan Prize would be financed by the US Government through legislation, and would ensure that public funds which go into a Mars mission are limited. It is a tiered prize system, with each tier progressively building technologies required to place humans on Mars and successfully return them to Earth. Zubrin's original concept follows:[191]

Challenge 1: Mars orbiter imaging mission

Prize: $500 Million

Conditions: Image at least 10 percent of Mars from orbit with a resolution of 10 cm per pixel or better.[192]

Bonus: Additional $1 million for imaging each of the 200 sites of interest selected by NASA's Mars Science Working Group.

Challenge 2: Mars sample return using Martian derived propellant

Prize: $1 billion

Conditions: Return at least 3 kg of Martian soil to Earth. At least 70% (by weight) of propellants used for the return leg must be produced from Martian resources.

Bonus: $10 million for each distinct rock type returned, up to a maximum of $300 million.

Challenge 3: Demonstrate long term life support in space

Prize: $1 billion

Conditions: A crew of three or more must be sustained in space for at least two years with no resupply from Earth.

Challenge 4: Deliver a pressurized rover to Mars

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[191] Zubrin, *Case for Mars*, 311-14.
[192] Subsequently accomplished by NASA's Mars Reconnaissance Orbiter. The cost of that mission was $720 million.

Prize: $1 billion

Conditions: Vehicle must be capable of sustaining two humans on Mars for at least one week, demonstrated by a one week test on Earth. The vehicle will be driven at least 1,000 km over unimproved terrain during the Earth test. The vehicle must travel at least 100 km on Mars while maintaining cabin pressure between 3 and 15 psi and temperature between 10° and 30° C.

Challenge 5: Demonstrate a system that can lift 5 tonnes from Martian surface to orbit using Martian derived propellants.

Prize: $1 billion

Conditions: At least 70% (by weight) of the propellant must be of Martian origin.

Challenge 6: Demonstrate a system which can produce more than 20 tonnes of propellant on the Martian surface during a 500-day stay.

Prize: $1 billion

Conditions: At least 70% (by weight) of the propellant must be of Martian origin.

Challenge 7: Demonstrate a system capable of producing at least 15 kilowatts power (day/night average) for at least 500 days on Mars.

Prize: $1 billion

Conditions: At least 2 kWe must be available at all times.

Challenge 8: Demonstrate a system which can deliver 10 tonnes of payload to the Martian surface.

Prize: $2 billion

Conditions: The system must provide a soft landing at Mars, providing no more than 8g deceleration on the payload during any portion of the trip.

Challenge 9: Demonstrate a system which can lift at least 120 tonnes to LEO.

Prize: $2 billion

Conditions: The system must launch from US territory. Past history of the Saturn V is not eligible. A revived Saturn V is eligible.

Challenge 10: Demonstrate a system that can put 50 tonnes onto a trans-Mars trajectory.

Prize: $3 billion

Conditions: Earth departure velocity must be at least 4 km/sec. System must be launched on a booster capable of putting 120 tonnes in LEO. System must be launched from US territory.

Challenge 11: Demonstrate a system that can deliver 30 tonnes of payload to the Martian surface.

Prize: $5 billion

Conditions: System must make a soft landing, exerting no more than 8g of deceleration during any portion of the trip.

Challenge 12: Send a crew to Mars and return them safely to Earth.

Prize: $20 billion

Conditions: A majority of the crew must be American. At least three crew members must reach the Martian surface and remain on the planet for at least 100 days. One or more of the crew must make at least three overland trips of at least 50 km each from the landing site.

Bonus: In addition to the $20 billion, each of the crew will receive $1 million per person per day for time spent on the Martian surface, up to a maximum of $5 billion total for the crew.

Some challenges on this list may be encompassed by others. If a system were to accomplish two or more challenges simultaneously, the demonstrator would win all the prizes which they have completed challenges for on that mission. While $20 billion seems like a low price for a Mars mission, the goal in the competition is not to pay for an entire Mars mission, but to provide financial incentive to investors who will pay for it. If the final mission were to never take place, the cost to taxpayers would be nothing, as the prize would not be awarded. A plan such as this would inject much needed funds into technology development, even if a Mars mission never leaves the ground. The bonus for crew who go to Mars ensures that whomever makes that journey is well payed for their adventurousness, their time, and their families' time away from them. Those who make that first journey would return to Earth wealthy.[193]

Another way to provide capital for a potential Mars mission at little or no cost to taxpayers would be the passage of a Space Settlement Prize Act. The Space Settlement Prize Act is a piece of draft legislation which has been written and sponsored by the Space Settlement Institute. The Act would provide that any private entity which develops a base on a celestial object and provides paid shuttle service to that object to make a claim on the object based on the size. For the moon the claim would be 500,000 acres, whereas on Mars the claim would be in the range of 1 million acres. For smaller objects, the claim could engulf the entire object. Then the claimant would have the right to sell the property for future development.[194] This "land speculation" could provide the needed investment for a Mars mission, as it would provide real property in which to invest once the mission is successful and a base has been developed.

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[193] Ibid, 310 and 314-16.
[194] Alan Wasser, "Draft of an Act Recognizing the right of the first permanent settlers on the Moon or Mars to claim and trade private ownership of the real estate around them," Space Settlement Institute, April 2012, accessed April 29, 2017, http://www.spacesettlement.org/law/.

Meanwhile, it would provide guaranteed access to that property for a realistic price. On the surface, this plan seems to violate Art. 2 of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies ("Outer Space Treaty" or OST), a UN treaty passed in 1967. However, OST was written before the emergence of the space economy which developed in the late 1990's and 2000's. Moreover, OST prohibits national appropriation, not private ownership. If several countries were to pass similar Settlement Acts, this would give credence to any private corporation which claimed ownership following the guidelines of the Act.

Funding for a Mars mission remains one of the largest obstacles, with governments being unwilling to devote the needed resources to complete a mission in a reasonable timeframe. By passing legislation such as Carl Sagan Prize Act or the Space Settlement Prize Act, the US government could provide incentive for private investors to bring much needed funds into the space exploration sector. This has the possibility of bringing about a crewed Mars mission that much sooner.

Concerning radiation, while astronauts in transit will receive a higher than normal dose of radiation, it is such a small added risk that the more adventurous people who would sign up for such a trip would be more than willing to take the risk. Such radiation also has a risk of damaging electronics. This risk can be negated by constructing a "water wall" around the more sensitive electronics, such as redundant computer systems. The threat of GCR can be lessened by launching during the solar maximum, when the sun is producing more CME particles, which has been shown to reduce the amount of GCR within the solar system.[195]

[195] "Next Solar Maximum may be Safest Time for Manned Missions to Mars," NASA/SSERVI, accessed April 29, 2017, https://sservi.nasa.gov/articles/next-solar-maximum-may-be-safest-time-for-manned-missions-to-mars/.

Conclusion

Many existential questions will be answered by conducting thorough investigations of the Red Planet. “Is humanity alone, a cosmic mistake in an infinite, lifeless universe?” and “If life were to develop elsewhere in the universe, what would it look like?” are commonly put forth as the most compelling questions which Mars could potentially answer. Only human beings can effectively conduct the detailed experimentation and searching which will provide these answers.

Beyond the scientific and philosophical questions that will be answered by a journey to Mars, perhaps the most persuasive reason to go to Mars is the indelible human desire to explore. Humanity is not native to Earth, but to a small valley in Ethiopia. It has only been through inspiration, tenacity, and ingenuity that humankind has come to dominate the planet. Robert Zubrin has proposed that with the closing of the American frontier, as detailed by Frederick Jackson Turner in 1897, the United States and humanity has lost the greatest natural driving force for change: exploration. Zubrin opines that humanity has now reached a new phase that he has dubbed “*pax mundana*.”[196] To fight the natural human urge to explore will lead to the decline of humanity. This is much like the failure of the Ming Dynasty to continue the voyages of Zheng He in the 15th Century, which led to China being “discovered” by Europe. Yet, Zheng He’s voyages, if they had continued, could very well have found Europe long before Vasco de Gama sailed into the Indian Ocean in 1498. Finally, Zubrin likens this to the current situation in spaceflight. Humanity made major accomplishments in spaceflight in the 1960’s, then turned inward, not launching any human exploration mission beyond LEO since 1972. NASA and the other major agencies have coasted on their accomplishments and rested on their laurels since.[197]

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[196] Robert Zubrin, *Entering Space*, 14-15.
[197] Ibid, 18-20.

However, the tide is turning, as evidenced by the uptick in robotic missions to Mars and the plethora of Mars mission models that have been proposed in the past 20 years. Each robotic mission has had a goal of returning information which will be used to determine requirements for a human mission to Mars. The stage is now set for the greatest journey humanity has ever taken. With current and maturing technologies, that journey could begin within the next ten years. The three greatest challenges that await are: maintenance of crewmember health during the journey; funding the mission; and making the mission sustainable. New technologies and experiments have proven that each of these challenges is surmountable. What is lacking is funding, a problem that has yet to truly be addressed by the space agencies of the world. It is the author's final recommendation that a public-private partnership be developed to leverage NASA's knowledge of Mars and the alacrity and dexterity of private ventures to accomplish goals with more efficiency and more speed than bureaucratic institutions. Once funding is secured, the next step will be the mission. It will be long and dangerous, but it is only humanity's first step. For after Mars, the rest of the Solar System and the Galaxy await.

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