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Humans to Mars: A feasibility and cost–benefit analysis[☆]

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Abstract

Mars is a compelling astrobiological target, and a human mission would provide an opportunity to collect immense amounts of scientific data. Exploration alone, however, cannot justify the increased risk. Instead, three factors drive a human mission: economics, education, and exploration. A human mission has a unique potential to inspire the next generation of young people to enter critically needed science and engineering disciplines. A mission is economically feasible, and the research and development program put in place for a human mission would propel growth in related high-technology industries. The main hurdles are human physiological responses to 1–2 years of radiation and microgravity exposure. However, enabling technologies are sufficiently mature in these areas that they can be developed within a few decade timescale. Hence, the decision of whether or not to undertake a human mission to Mars is a political decision, and thus, educational and economic benefits are the crucial factors.

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1. Introduction

In the past decade, we have monitored the Martian weather, constructed a geologic history, are presently characterizing the radiation environment [1], and have learned that water ice is likely to be present underground [2]. Presently, NASA's Mars exploration program includes orbiters, rovers, and in the distant future, a sample return mission. However, we consider a new direction for Mars exploration: preparation for a *human* mission.

As a result of our analysis of the mission's technical and political feasibility, the 2002 Astrobiology Academy proposes that NASA adopt a human mission to Mars as a clear and articulated goal of the agency. Since the 1960s, NASA's paradigm has shifted from destination-focused missions, i.e. "We will put a man on the Moon", to research-driven goals, including space-based monitoring of Earth and the study of life in extreme environments. The Astrobiology Academy advocates a return to a more mission-centric NASA, namely a human mission to Mars, driven by scientific objectives. By coupling science to a human Mars mission, the United States will create a program of exploration that excites the world and is an investment, not only in basic scientific knowledge, but also in strengthening the global economy and creating technologies that improve life around the world.

Below we present a rationale for the choice of a human mission to Mars. Of all the world's space agencies, NASA is the one with the most mission experience; presently, it is the one most capable of initiating a human mission to Mars. For this reason, our analysis focuses on those factors which will enable NASA to undertake such a mission. We examine the state of science and engineering education in the US today, using reports from the National Science Foundation and Congressional commissions, and investigate the effects that a human mission to Mars would have on the science and engineering disciplines. We explore the likely costs of a human mission to Mars in the context of other federal expenditures. The extent of the research and development initiative that would be needed and "spinoff" technologies that might emerge from a human mission are identified. Throughout, we assess the advantages and disadvantages of going to Mars, focusing not only on the science benefits of a human mission, but on broader societal implications.

2. Exploration

2.1. Why Mars?

Mars presents a feasible destination by virtue of its relative proximity to Earth and its analogous surface conditions. It has neither the crushing gravity nor the noxious atmosphere that make human exploration of other solar system bodies all but impossible. Furthermore, Mars is a compelling target that is both scientifically interesting and appealing to the public at large. Since earliest Greek mythology, Mars has intrigued humans and continues to do so as evidenced by numerous recent "pop-culture" movies and books. Four decades of US and Russian robotic exploration have led us to understand that Mars, at least in the past, was a planet not very different from our own.

The robotic science program has focused on understanding Mars' geologic and climatic past, especially understanding why it diverged from that of Earth. The current strategy of NASA Mars exploration is "Follow the Water". Liquid water is essential to living organisms, and the history of a planet's water is used to assess paleohabitability. We are relatively certain that Mars' climate several billion years ago was warm enough that liquid water would have existed on the surface (e.g. [3 and 4]). This may have been the case even within the past few million years due to periodic obliquity changes in the orientation of Mars' axis [5]. Recent Mars Global Surveyor and Mars Odyssey data have shown that liquid water may be present ephemerally on the surface today as discharge into gullies [6] or meltwater in snowpacks [7]. Frozen water has also been found in the top one meter of soil at abundances of up to 35% [1].

On Earth over the past several decades, researchers of life in extreme environments have found microbes growing in quite inhospitable conditions, indeed, almost anywhere that liquid water is present [8]. Coupled with what we now know of the abundance of water on Mars, this suggests that life was, and is, possible on Mars. Additionally, the study of Mars habitability helps us to answer the fundamental questions "Where did we come from?" and "Are we alone?" and to understand better those factors shaping the history of life on our own planet. Mars is then an ideal target for NASA exploration.

2.2. Why humans?

It is argued that machined missions are less expensive and are thus the preferred method of exploration, following the NASA's former "faster, cheaper, and better" motto. However, if machined missions are subject to technical limitations and fail to inspire the next generation of scientists and engineers, then are they really the better method of exploration?

Even as machines become more autonomous and self-sustaining, a machine will not soon have the ability to behave as an innovative and adaptive scientist, quickly synthesizing information and shifting from one pursuit to another [9]. With training, a human can operate tens to hundreds of pieces of equipment. This can be compared to the Mars Exploration Rovers that landed in 2004 and carry a payload of five scientific instruments and a rock abrasion tool. By virtue of superior mobility, planning and analytical capability, and an ability to shift context, for example from microscopic sand grains to cliff rock strata, a human Mars explorer would greatly increase scientific data volume. Sending humans does increase the magnitude of the negative effects of a mission failure, however. This fact increases the hesitancy of political leaders to underwrite a mission. For that reason, further justification for a human mission to Mars than simply science objectives is required.

3. Education

Educating and inspiring America's youth has long been a priority of NASA. Hence, we investigate the likely effects of a human mission to Mars on education in the United States.

The Bureau of Labor predicts a 20% employment increase in engineering and a 15% increase in the physical sciences in the next 10 years, but as the Hart–Rudman Commission report states simply, the "US need for the highest quality human capital in science, mathematics, and engineering is not being met" [10]. In physics and advanced mathematics, American seniors score significantly below the international average on tests. While this is usually attributed to problems within the schools themselves, a general disinterest in math and science also contributes to American high school students' poor performance.

The trend continues at the undergraduate level. Comparing degrees granted between 1975 and 1999, the United States has a poor percentage increase compared to other nations. This decline is also reflected in the downward trend of the US relative to other nations in science and engineering degrees granted per capita to 24-year-olds [10]. At the graduate level, it is apparent that the number of doctoral degrees in natural sciences and engineering attained in Europe and Asia has increased rapidly compared to that of the United States. In 1975, the US granted approximately 13,000 science and engineering doctoral degrees compared to Europe's 7,000 and Asia's 4500. In 1999, the US granted approximately 18,000 science and engineering Ph.D.s while Europe granted 23,000 and Asia 19,000 [10]. Additionally, within US universities, 25% of graduate students in the sciences and nearly 40% of the graduate students in engineering, mathematics, and computer science are foreign born [10]. Based on this data, we see that decreasing production of scientists and engineers is not a global trend, but an area of particular concern for policy-makers in the United States.

Some argue that money put into the space program could be better spent by putting it directly into the educational system to encourage students in the sciences and engineering. This is an unfortunate misconception. The United States is already one of the top spenders per student in the world [10]. Although more funding could always be useful to the American educational system, it does not promise the sustained effort needed to increase the number of Americans pursuing advanced degrees in science or engineering. The government cannot simply buy more computers, fund more scholarships, and lower teacher-to-student ratios enough to convince an 18-year-old freshman to invest at least 8 years in the pursuit of a science and engineering advanced degree. Students need something to inspire their efforts.

The idea of space exploration significantly influencing youth is not without precedent. During the Apollo era of the 1960s, there was a dramatic increase in the number of American students pursuing advanced degrees in science, math, and engineering shortly after President Kennedy's initiation of the Apollo program (Fig. 1). Furthermore, after the Apollo program was dismantled and NASA's funding cut, the number of students going into these fields decreased with a down-

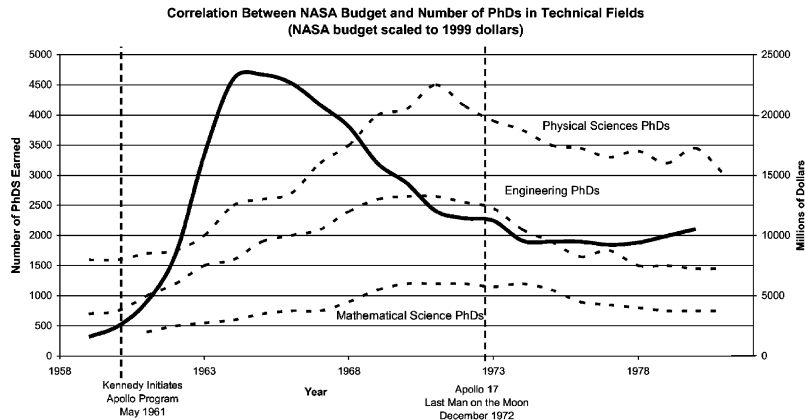


Fig. 1. NASA Budget and Technical Ph.D.s. An increase in the number of science and engineering Ph.D.s [10] is concurrent with the rise of NASA budget [26]. Note that the 9 year lag time in maxima is equivalent to the education time from high school senior to Ph.D.

ward trend of NASA's budget. The figure is only a correlation; numerous other significant historical events, including the Vietnam War, also occurred at this time. However, anecdotal accounts of science and engineering professionals entering their disciplines inspired by the Apollo program "To the Moon" goal indicate how NASA can inspire a generation.

Indeed, "To inspire the next generation of human explorers" [11] is the most compelling reason for the US policy-makers to support a human mission to Mars. The United States counts on advanced technology for economic stability and national security, which in turn depends on the ability of American universities to supply the science and engineering workforce. As the technological demands of the American lifestyle steadily increase, inspiration of the next generation of scientists and engineers becomes critical. A human mission to Mars has the unique ability to invigorate future scientists and engineers and create a program that operates in tandem with existing educational programs, adding an inspirational vision to supplement the efforts of teachers.

4. Economics: costs–benefits

4.1. What is the cost?

One common argument against a human mission to Mars is the expense. We will not attempt to put a price tag on a mission in this document since such a figure requires a detailed mission architecture, but

it is instructive to place a range of cost estimates in context. In general, costs for a human Mars mission range from a low of \$20 billion [12] to a high of \$450 billion [13]. The latter estimate includes use of the moon as a launch point. Here we examine the relative costs of each by assuming an order of magnitude price range, between \$30 billion and \$300 billion.

The lower number represents twice NASA's annual budget of about \$15 billion [14]. If we spread human Mars mission costs over ten years, this would account for only 20% of NASA's annual budget per year, spending \$3 billion per year. The current budget for the Mars Exploration Program is 15% of this value, at about \$450 million per year [14]. Placing mission cost in a different context, the annual cost of the high-end number, spread over 30 years, is approximately the same amount that the tobacco industry spends on advertising each year, around \$8.2 billion [15].

A commonly expressed fear is that money for a Mars mission would take away money from the human services sector. The budget for the Department of Health and Human Services (HHS) tallies almost \$490 billion annually, with a FY2003 increase of 6.3%. The HHS increase alone, \$30 billion FY2003, is equivalent to the low-end cost estimate of a human Mars mission. Putting it another way, a Mars mission would be cost-equivalent to 0.5% of the HHS annual budget. We conclude then that a human mission to Mars is not barred by cost considerations. Indeed, cost is relatively small compared to other federal government endeavors and the mission's considerable benefits.

Table 1
Areas of technology development from a human Mars mission [27]

Challenge to a human Mars mission	Technology development	Terrestrial applications
Harmful effects of microgravity and radiation on human health.	Pharmacological and mechanical prevention treatments.	Prevention, detection, and treatment of illnesses ranging from osteoporosis to cancer.
Limited air, water, and food resources.	Closed loop life-support systems.	Conservation, recycling, waste management.
Limited energy supply.	Alternative energy sources low energy-use technologies.	Renewable efficient energy sources; energy-conserving consumer products.
Human safety and health is threatened in space.	Automation and robotics.	Remote or automated robotics to reduce human risk in hazardous environments.
Hardware impaired by extreme conditions of space.	Extended life, low maintenance materials, hardware, and systems.	Stronger, smaller, more reliable products for consumers.

4.2. What are the benefits?

The health of a nation's economy and its international competitiveness are in part a measure of the national investment in research and development in science and engineering. NASA has devoted its facilities, labor force, and expertise to generating innovative technologies that overcome the challenges of space and to sharing mission technologies with US industries [16]. These countless technologies have successfully contributed to the growth of the US economy. For example, satellite technology has created an \$85 billion industry that improves our daily lives through a myriad of communication, navigation, and weather-forecasting services [17].

A human Mars mission would direct and focus the resources and infrastructure of NASA into the research and development of the high-technology industries listed in Table 1. The product of these investments in innovation would result in gains in the US market share, create new markets, use resources more productively, expand business, and create high-wage jobs (e.g. [10,18]). Such technologies also have the potential to improve the quality of life throughout the world.

5. Feasibility analysis

5.1. Propulsion and transit times

Orbital and landing craft have been developed for human lunar missions; however, the creation of interplanetary propulsion for a human system is a new un-

dertaking. Propulsion is central to the success of any planned Mars mission, and minimizing transit time will limit astronaut exposure to radiation and microgravity. More fuel is required to increase the speed of the rocket, but additional fuel also increases the spacecraft mass and thus the launch cost. Liquid, solid, and nuclear propulsion technologies are all sufficiently well-understood that they could be further developed and employed for a propulsion system. An optimum trade-off between cost and transit time (one-way trip times range from a month to a year) must be selected [19]. Techniques such as aerobraking and a split mission architecture, where cargo is sent first and astronauts are sent later on a faster spacecraft, can be utilized to reduce fuel costs and increase speed of transit. The use of Mars carbon dioxide to produce return fuel has also been pilot tested [12].

5.2. Hazards

Some argue that a human mission to Mars is not within our current technological capabilities. Before a human crew is sent on a voyage to Mars, NASA must ensure that it can adequately protect astronauts from health hazards they face on the journey, such as radiation exposure and prolonged microgravity conditions, and prevent planetary cross-contamination by microorganisms. Below, we discuss these oft-cited hazards and address the technologies needed to overcome them. We further explore how investigations into the effects of space travel on the human body may lead to new technological advances here on Earth.

5.2.1. Radiation Exposure

Once astronauts leave Earth orbit, protective measures are necessary to block ubiquitous galactic cosmic rays and high-intensity bursts of radiation resulting from solar proton events [20]. The Martian Radiation Environment Experiment (MARIE) on the Mars Odyssey spacecraft has measured radiation levels both in transit between Earth and Mars and within lower Mars orbit. Radiation above Mars is about 2.5 times that in the International Space Station, though levels received by a crew member over the duration of a Mars mission would not exceed NASA career dose limits [1].

Several shielding technologies exist to address radiation challenges. Passive shielding employs no energy but uses an enormous shielding mass of hydrogen in the form of water. This passive shielding unfortunately increases mission costs by increasing payload size. Active shielding methods, which work in much the same way as the Earth's electromagnetic field by deflecting interstellar charged particles, are promising alternatives but have a failure risk and require energy [20]. A hybrid system combining aspects from both types of shielding optimizes both the level of protection afforded to the crew and the size of the payload mass. Certain types of shielding technology are nearing maturity given what we know about the radiation environment; however, we agree with the recommendations of others [21,22] that further radiation level measurements on Mars' surface are needed.

5.2.2. Microgravity

In the course of a human mission to Mars, the crew will experience the zero-gravity environment of interplanetary space, the 0.38g environment of Mars, the zero gravity of space on the return trip, and a return to normal Earth gravity. Research on microgravity effects has been conducted using space-based data as well as ground-based simulations like water immersion. Pharmaceuticals, exercise, conditioning, and artificial gravity are promising strategies that mitigate the effects of microgravity on humans in space. Exercise and conditioning are considered effective means of countering the physiological effects of microgravity, though the amount of time devoted to an exercise program must be weighed against time taken away from required daily tasks and functions.

Another possible countermeasure is the production of artificial gravity by techniques ranging from suits worn by astronauts that provide magnetic or pressure loading, to spacecraft centrifuges [12,20]. A rotational spacecraft shows the most promise by providing a constant gravity environment. Pharmaceutical research is also ongoing. For example, hibernating bears produce a regulatory substance similar to a human bone-growth factor that promotes the formation of bone despite the absence of mechanical skeletal loading [20]. If we can isolate and replicate this substance, it may be useful both in treating bone demineralization in space and helping to treat or prevent osteoporosis here on Earth.

5.2.3. Avoiding cross contamination

Robotic missions to Mars already have strict Planetary Protection protocols. Protection strategies developed for a human Mars mission will be even more stringent and have important applications outside of the space program. Clean room and sterilization research will help us to understand and cope with the continuing mutation and evolution of pathogens in our hospitals. Technologies developed will aid in our attempts to prevent the movement of pathogens such as the malarial parasite and West Nile virus into higher latitudes and combat biological terrorism. These are clearly important investments for the United States to make in the next decade.

5.2.4. International Cooperation

While there are some inherent difficulties to international efforts—variable and uncertain funding, communication problems, and technical interfacing difficulties—these problems will be outweighed by the tremendous worldwide benefits associated with an international endeavor to Mars. The experience of other space-faring nations exceeds that of the United States in specific technical areas, e.g. the Canadians in large-scale robotics and the Russians in extended duration human space flight and heavy-lift rocketry. Thus, it is nearly inevitable that a NASA-directed human mission to Mars would have international partners.

A United States commitment to leading a human Mars mission would have substantial positive repercussions in international relations. Despite the incredible achievements of the Apollo program, the program did have shortcomings. The primary (some say

the only) goal of the Apollo program was that the United States beat the Soviets to the moon. In retrospect, a more long-term planning effort for exploration might have allowed a permanent human presence on the moon or its use as a stepping point to other destinations in the solar system. An international human mission to Mars has the potential to be a more sustained exploration effort because it will not be subject to the whims of a single nation. Other nations have expressed their desire for a human mission to Mars, including Russia [23], China [24], and the European Space Agency in their Aurora program, which indicates that the US will have eager allies if it chooses to undertake a human mission.

6. Conclusions

We have shown that exploration, education, and economics are the driving factors justifying a human mission to Mars. A human mission to Mars is technologically feasible, cost effective, and safe for our astronauts. The scientific findings that would result are significant. However, far more compelling to US policy-makers is the mission's benefit to the future of the United States as a nation since the mission would be generating innovative technologies, improving international relations, and inspiring the scientists and engineers of the next generation. This would be done at a relatively small cost.

There will be challenges, some of which we cannot fully evaluate until we have embarked on a mission. The technological aspects can be planned and debated only to a certain point in advance. The way to develop a technology is to actually invest resources and begin developing it. By setting the goal of a human mission to Mars, the development process can begin for the technologies that will actually take us there. This goal-driven developmental concept extends back to the Apollo era in a prescient analysis by the Space Studies Board examining the feasibility of a human mission to the Moon. They concluded that unless humans are explicitly included in the technical planning for exploration of solar system bodies, they inevitably will be excluded because the measures necessary to ensure their safety will not have been addressed [25]. Hence, unless humans are explicitly designated as an essential part of the NASA Mars exploration strategy,

the technologies needed for them to make the Mars trip are unlikely to be developed. Thus, we urge that NASA in conjunction with the international community begin planning now for a human landing on Mars within the next few decades.

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