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*Future Visions for Scientific Human  
Exploration—James Garvin*



*An artist's conception of a future base and astronauts on Mars. This NASA image was produced for NASA by Pat Rawlings.*

Human exploration has always played a vital role within NASA, in spite of current perceptions that today it is adrift as a consequence of the resource challenges associated with construction and operation of the International Space Station (ISS). On the basis of the significance of human spaceflight within NASA's overall mission, periodic evaluation of its strategic position has been conducted by various groups, most recently exemplified by the recent Human Exploration and Development of Space Enterprise Strategic Plan. While such reports paint one potential future pathway, they are necessarily constrained by the ground rules and assumptions under which they are developed. An alternate approach, involving a small team of individuals selected as "brainstormers," has been ongoing within NASA for the past two years in an effort to capture a *vision* of a long-term future for human spaceflight not limited by nearer-term "point design" solutions. This paper describes the guiding principles and concepts developed by this team. It is not intended to represent an implementation plan, but rather one perspective on what could result as human beings extend their range of experience in spaceflight beyond today's beach-head of low-Earth orbit (LEO).

Exploration of unknown frontiers has captivated the human spirit since the dawn of time, and it has been suggested that this spirit embodied the settlement and ultimately the development of the American continent and culture. How this concept has been extended to the space environment has largely been the stuff of science fiction, with the exception of the remarkable voyages of human beings to the Moon as part of NASA's Apollo Program. It is humbling to note that it has been

more than twenty-eight years since humans have broken the bounds of the Earth's gravity field and physically entered the deep-space environment. Contrary to the misconceptions of many, the human experience in the space environment beyond the protective shielding of the Earth's Van Allen radiation belts is limited in its entirety to the brief flights of Apollo 8, 10, 11–17. Only approximately 220 hours of extravehicular activity (EVA) time was conducted by the Apollo explorers who visited the lunar surface between 1969 and 1972. Given this sometimes forgotten legacy, one quickly recognizes the extreme challenges of safely moving human explorers “on site” within deep space. This has posed a fundamental challenge to NASA in spite of the spectacular and perhaps unrivalled success of the Apollo Program of thirty years ago.

NASA has recognized the challenges of human exploration of deep space (HEDS) and most recently formed a small team of scientists, systems engineers, project managers, and biomedical experts to develop a vision with a somewhat radical set of boundary conditions. The challenge given to this wholly internal NASA exploration team was to develop a *scientifically driven* vision, enabled by new technologies and resource-constrained to eventually be implemented in an incremental fashion, rather than requiring a large total investment at the outset. The requirement that human exploration in this vision be driven by science and how human beings within deep space can uniquely contribute to the furthering of scientific progress is unprecedented. While the human spaceflight activities planned (and underway) on the ISS are certainly linked to fundamental scientific challenges, the

broader scientific community has argued that the overriding motivation for the ISS in the first place was not as the logical next step for conducting high-priority scientific investigations from the vantage point of space. For example, the scientific catalysts for the ISS were not linked directly to the driving science challenges articulated by NASA's Earth and Space Science Enterprises. Ultimately, of course, the experience with long-term human adaptation to the near-Earth space environment and microgravity . . . provided by the ISS is a necessary stepping stone for humans to re-enter the deep-space environment as scientific explorers.

The challenge of science-driven human exploration is to develop the traceability from the most imposing scientific questions to human "on site" activities that will dramatically increase the potential for major discoveries and progress. The links between what humans can potentially accomplish by "being there" versus what can be achieved with high-bandwidth telerobotic presence (i.e., vicarious presence on site by humans off site) can be simply articulated. Our existing experience with human activities in space suggests that human-based field studies, provided robotic adjuncts are available to offer assistance and other infrastructure, are uniquely "discovery oriented," making possible rapid progress because of dynamic in-the-field responses to the local environment. The Apollo human expeditions demonstrated a high degree of onsite responsiveness to the lunar geologic environment, allowing for nearly instantaneous adjustments, thereby improving the field sampling results. In addition, humans can serve as effective erectors and operators of sophisticated apparatus in complex

field environments. The Apollo experience again demonstrated the value of human-based setup of field geophysical equipment that even today defies our purely robotic capabilities. Thus, deriving the activity breakdown structure that optimizes insertion of the human into the scientific process is a key element of the vision recommendation for science-driven human exploration. Today, humans explore deep-space locations such as Mars, asteroids, and beyond, vicariously here on Earth, with noteworthy success. However, to achieve the revolutionary breakthroughs that have punctuated the history of science since the dawn of the Space Age has always required humans as “the discoverers,” as Daniel Boorstin contends in this book of the same name.<sup>1</sup> During Apollo 17, human explorers on the lunar surface discovered the “genesis rock,” orange glass, and humans in space revamped the optically crippled Hubble Space Telescope to enable some of the greatest astronomical discoveries of all time. Science-driven human exploration is about developing the opportunities for such events, perhaps associated with challenging problems such as whether we can identify life beyond Earth within the universe.

At issue, however, is how to safely insert humans and the spaceflight systems required to allow humans to operate as they do best in the hostile environment of deep space. The first issue is minimizing the problems associated with human adaptation to

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1. Daniel J. Boorstin, *The Discoverers: A History of Man's Search to Know His World and Himself* (Random House: 1983).

the most challenging aspects of deep space—space radiation and microgravity (or non-Earth gravity). One solution path is to develop technologies that allow for minimization of the exposure time of people to deep space, as was accomplished in Apollo. For a mission to the planet Mars, this might entail new technological solutions for in-space propulsion that would make possible time-minimized transfers to and from Mars. The problem of rapid, reliable in-space transportation is challenged by the celestial mechanics of moving in space and the so-called “rocket equation.” To travel to Mars from Earth in less than the time fuel-minimizing trajectories allow (i.e., Hohmann transfers) requires an exponential increase in the amount of fuel. Thus, month-long transits would require a mass of fuel as large as the dry mass of the ISS, assuming the existence of continuous acceleration engines. This raises the largest technological stumbling block to moving humans on site as deep-space explorers—delivering the masses required for human spaceflight systems to LEO or other Earth orbital vantage points using the existing or projected fleet of Earth-to-orbit (ETO) launch vehicles. Without a return to Saturn V-class boosters or an alternate path, one cannot imagine emplacing the masses that would be required for any deep-space voyage without a prohibitive number of Shuttle-class launches. One futurist solution might involve mass launch systems that could be used to move the consumables, including fuel, water, food, and building materials, to LEO in pieces rather than launching integrated systems. This approach would necessitate the development of robotic assembly and fuel-storage systems in Earth orbit, but could provide for a natural separation of low-value cargo (e.g., fuel, water) and

highly sensitive cargo (i.e., humans and their associated systems and science tools). Future mass launch possibilities, including innovative laser levitation systems, beamed energy approaches, and even giant sling-based systems, could deliver the insensitive cargoes out of the Earth's gravity well at costs ultimately less than \$100/lb, opening up new launch industries and distributing the launch requirements. Future-generation reusable vehicles could then concentrate on high-value payloads (humans, etc.) only and not have to carry low-value but high-volume materials all as part of the same system.

The new vision that emerges challenges the existing paradigms associated with ETO, in-space propulsion, as well as the types of trajectories to be used. Today we can hardly imagine hyperbolic, non-Keplerian transfers from Earth to deep-space destinations due to the unimaginable fuel mass requirements and in-space propulsion system performance levels. However, concepts for fusion-based propulsion could, in theory, deliver human-class systems from Earth to Mars in as short as ten days, and innovative ETO solutions are under study that might someday launch 1000-kg. cargoes to LEO for less than \$100/lb and store consumables there in depots. This type of distributed approach would obviously require concerted investment and development, but, in theory, it could facilitate shorter-duration scientific exploration missions for humans to destinations as distant as the asteroid belt, Mars, or near-Earth objects such as comets and asteroids.

Any vision for scientific exploration of deep space by humans must always confront the issue of human safety and accessibility to the environment to be explored. It may be worthwhile to send



human explorers hundreds of millions of kilometers to Mars orbit only to teleoperate robotic explorers on the planet's surface, but that would ultimately diminish the science "discovery" potential of humans on site. Human adaptation to deep space requires shielding or other countermeasures associated with space radiation, variable gravity, psychological stress, closed life support, and telemedicine. Materials science breakthroughs, as well as more effective space power systems, may ultimately provide the technological catalysts required. Carbon nanotubes (CNT) may deliver amazing strength-to-weight possibilities, thereby enabling structures hundreds of times less massive and contributing to shielding for human voyagers. Quantum energy delivery space power systems could provide kilowatts to megawatts of reliable power to sustain human crews and to power surface-based exploration. For example, on Mars there is an emerging requirement to access the subsurface to regions where liquid water may be stored. Such regions may lay hundreds to thousands of meters below the surface and necessitate complex drilling operations, all of which would require abundant and sustained power, as well as human tending.

The vision for human exploration considered by the NASA brainstorming team identified several breakthrough technology areas for which order-of-magnitude improvements over the existing evolutionary pace of development will be required to cost-effectively send humans into deep space with scientific activities in mind. Point design solutions certainly exist today that suggest there may be other nearer-term implementation solutions. However, if the overarching aim is to enable humans

to conduct science operations on site in deep space, then technological breakthroughs that will have near-term robotic benefits are clearly needed. Aside for a few breakthrough technologies, there exists a thematically organized set of evolutionary technologies that must be matured if sustained human spaceflight beyond LEO is to be achieved. These include closed life support, telemedicine, information technology (automated vehicle health and maintenance), power delivery systems, artificial gravity, EVA systems, and human-robotic adjuncts and associated investigative sensors.

The science-driven, technology-enabled vision, as described above, would delay ambitious human-based deep-space exploration until sufficient technological breakthroughs are in hand to follow the guiding principles and ground rules. As a case example, we will consider scientific exploration of Mars by human beings as embodied by this technology-rich vision. In this case, a cascade of robotic forerunners integrated with NASA's ongoing robotic Mars exploration program would demonstrate the surface technologies and develop the required knowledge base about Mars and its environment before humans would be inserted on the surface. Initial human-based Mars exploration would be tactical, making use of the wealth of reconnaissance from precursor missions to focus on a few key sites at local scales with very goal-driven field exploration strategies. Initial tactical visits would be limited to six to nine months roundtrip, enabled by a new generation of in-space transportation systems, and involve surface residence times of thirty to forty days. These initial scientific expeditions might resemble the ongoing field

exploration of the Earth's polar regions in which human explorers venture to a few key localities for very constrained periods of time but study the region from safe habitats telerobotically before conducting their optimized EVAs. First-visit human activities would be focused on highly informed sample collection, subsurface access, and on in-the-field-based discoveries. In addition, such initial human explorers would naturally serve as erectors of complex in situ geophysical and biogeochemical instruments and experiments which would operate long after the humans return to Earth. This sort of leave-behind infrastructure would be a vital part of the first wave of local, targeted human exploration, paving the way for longer-duration scientific outposts at the most promising sites. Initial visits would necessarily involve limited EVA activities, perhaps at the same level as those associated with the Apollo J-series missions (i.e., 7 hours per day). Conducting in situ life-detection experiments on possibly biologically related materials assuming appropriate safeguards may also emerge as key activities of the initial campaign of human visits.

The first wave of human expeditions would ultimately give way to a more sustained presence, with operations that could resemble those at Antarctic outposts here on Earth. Most importantly, as enabling technologies mature, human access to a variety of deep-space locations, including global access to the Martian surface, will be facilitated. Sending tactical, human onsite missions to targets where the scientific action has been identified by virtue of robotic precursors is an ultimate objective. In this vision, one can imagine a series of human-tended Martian surface drilling sites and associated astrobiology laboratories in which

the chemical fingerprints of life are explored in situ, without the challenges of planetary protection (i.e., associated with returning samples of volatile materials to Earth safely, with no threats of backward contamination). Other possibilities might involve human field exploration of main-belt asteroids that could harbor evidence of ancient liquid water and potentially prebiotic indicators. Finally, there are scenarios in which human global access to the lunar surface would facilitate a series of sample return missions with which to determine the absolute chronology of the early-time portion of solar system history, and perhaps to link it with Earth, Mars, Mercury, and other objects.

This example vision might be viewed as an unwinding spiral of coupled scientific and technological developments that set the stage for an ever-increasing scope of human scientific activities at a wide variety of destinations in deep space. Discovering the limits of our science knowledge catalyzed by pushing the boundaries of our technological developments would offer a rich array of opportunities for engaging people, the ultimate customers of our deep-space exploration. This vision is all about using technology to dramatically amplify what we can learn scientifically and to facilitate a pace of discovery that provides excitement, adventure, and educational opportunities. By aggressively pursuing new technologies, the potential for feedback of such technologies into more traditional NASA programs, as well as to closer-to-home problems, would be maximized.

As with any vision, there are recognized implementation challenges. Moving human vehicles to Mars on time frames as short as weeks could require masses of fuel as large as asteroids,

if one is not careful. Mass launch scenarios that require aggregation of hundreds to thousands of elements or fuel containers are almost unimaginable by today's standards. However, it is humbling to recall the lessons of history. In only twenty years after the voyages of Columbus and other early Renaissance explorers to America, Magellan and his team successfully circumnavigated planet Earth. Where could we be in twenty years with a sustained, integrated effort in which science, technology, and the adventure of human spaceflight work together? The possibilities are many, and what has been described here is one viewpoint developed during the course of an eighteen-month study by a single team of brainstormers. Our aim is to enable human exploration, and this vision is but one tale of a future that could be.

