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Rovers in the U.S. Mars Exploration Program

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ABSTRACT

The U.S. Mars Exploration Program comprises at least one Discovery mission (Mars Pathfinder), and the Mars Surveyor Program, plus sample return missions and other missions to prepare for possible human expeditions to Mars, The original themes of the Mars Surveyor Program (which are still the official program goals) are to understand Life, Climate and Resources on Mars, with these themes tied together by the common thread of Water. The program will launch (on average) two missions every 26 months. The missions launched between 1996 and 2001 will include a lander and an orbiter at each opportunity, launched on the Delta family of launch vehicles, International participation is an important factor in the program, and relationships are being established with Russia, Europe and Japan. The program is severely cost constrained, with missions costing about $ 150M apiece or less, including launch and operations.

The ability to move about the Martian surface is key to the Mars Exploration Program. This paper addresses the overall Mars Exploration Program strategy, with an emphasis of the role of rovers in the program, Specifically, the need for improvements in rover performance is addressed,

Historic Background

In 1965 Mariner 4 flew past the southern part of Mars and sent back pictures of an ancient, heavily cratered terrain, apparently moonlike and lifeless. Two flybys in 1969 also imaged the same part of Mars. But in 1971 Mariner 9, and later the Viking orbiters in 1976, discovered a vastly more interesting view of Mars,

Mars was found to be a planet of stark contrasts. Viewed from orbit the surface features range from ancient, cratered terrain like Earth's moon, to giant volcanoes, to a canyon as long as the United States is wide and five times as deep as the Grand Canyon, indicating that Mars was much more geologically active than the moon, It's only 1/8 as massive as Earth, but it has as much dry land area as Earth because Mars has no oceans. There's evidence that water once flowed and cut channels on the surface four billion years ago. But the surface is now dry except for two constant polar caps with reservoirs of water ice, some thin water-ice clouds, and a periodic dusting of frost. After Mariner 9, it was thought that life might have developed during a wetter time on Mars, and might even still be present in the soil.

Close-up on the surface, as revealed by two Viking landers in 1976, Mars resembles an earthly desert like California's Mojave. The Viking landers carried experiments to look for life in the top layer of Martian soil. The results were disappointing. This layer has apparently been sterilized, probably by the ultraviolet light which is hardly diminished by the thin Martian atmosphere. In addition, atmospheric conditions at the surface of Mars are not very friendly for life, The atmosphere is less than 1% as dense as Earth's and is almost all carbon dioxide. It's cold on Mars, especially in northern winter. The northern polar cap is mostly made of dry ice that condenses from the air, although there is considerable water ice in both poles.

Mars is a difficult planet to study. The United States has lost three Mars spacecraft before they reached the planet. The Russians have also failed on several attempts at Mars (although they have been very successful at Venus). Their most recent failure was that of Mars 96, an ambitious, multi-national endeavor which was to have orbited Mars and landed four elements. In 1992 the U.S. sent a large mission called Mars Observer. Just as it was about to go into orbit around Mars contact was lost, and it has never been heard from again. This was the first loss of a U.S. planetary spacecraft in 25 years.

But out of the ashes of the Mars Observer failure arose, Phoenix-like, a long term "program" for exploring Mars. The initial goals of this currently funded Mars Surveyor Program are to understand Life, Climate and Resources on Mars, with these themes tied together by the common thread of Water. Water is vital for life (either past Martian or future human), and drives the planet's climate. The Mars Surveyor Program is designed to look for signs of pastor present water, to understand the conditions under which life might have formed, and to understand how the climate of Mars evolved over the 4.5 billion years of its history.

The Current Mars Exploration Program

The program is currently planned to launch (on average) two missions to Mars every 26 months. The missions launched in 1996 and 1998 will include a lander and an orbiter at each opportunity, and all missions are currently planned to be launched on a family of relatively small, inexpensive launch vehicles. The Mars Global Surveyor mission was launched in November 1996, carrying copies of six of the eight instruments which were lost with Mars Observer. Mars Global Surveyor will go into orbit around Mars in September 1997 and will map the surface and atmosphere for a full Martian year (two Earth years), The Mars Pathfinder mission (which is actually part of the Discovery Program rather than the Mars Surveyor Program) was launched in December 1996 and will land on the Martian surface on July 4, 1997 and deploy a small rover called Sojourner.

In 1998 an orbiter will carry a copy of the seventh Mars Observer instrument and a lander will explore the layered terrain near the south pole with a robotic arm. Also in 1998 the Japanese will launch an aeronomy orbiter to study the upper atmosphere.

After 1996 U.S. Mars missions will be launched on "Med-Lite" (McDonnell Douglas Delta 7325 or 7425 class) launch vehicles. These can throw between 500 and 700 kg to Mars, depending on the opportunity. Total costs of the Mars Exploration Program are restricted to about $ 150M per year, including launch vehicles and operations (about the price of a major motion picture or theme park ride). The program is precluded from using nuclear power and is committed to planetary protection.

A strategy for the U.S. Mars Exploration Program has been developed involving - in addition to the selection of a science theme for the program - a long-term industrial partnership for spacecraft development, continuous infusion of new technology, integration of the individual projects into an overall program so that synergy between projects can be maximized, and the use of opportunities for international collaboration. A number of new management techniques are being used to carry out an ambitious science program within the funding constraints.

The original goal for the 2001 landed mission was to continue the "volatiles and climate" theme established by the Mars Science Working Group in 1994-95. The 2001 lander was to include a rover to analyze rocks in the ancient highlands to understand the climate history of Mars. A possibility was identified for the rover to be landed in or near an ancient lake bed to study sedimentary materials. 2001 was also to complete the work of the failed Mars Observer mission by flying a copy of its last instrument, with the others having been carried by the 1996 and 1998 orbiters,

However, in August 1996a NASA press conference was held announcing the discovery of possible evidence of past Martian life in a meteorite from Mars designated as **ALH84001** (because it was found in the **Allan** Hills region of Antarctica in 1984). As a result, a set of studies was initiated to develop a science strategy which would focus specifically on the search for past and present life on Mars. It is likely that the Mars Surveyor missions after 1998 give greater emphasis to this "life" strategy.

The basic science strategy for the search for Martian life comprises a phased program to maximize the chances that if pastor present life is there, it will be found, This strategy is based on **first** characterizing the planet from orbit to identify the most promising sites for later in-situ investigation with rover missions, These rovers would land and explore over tens of kilometers, analyzing and selecting samples for later return to Earth. Sample return missions would then be launched and would return samples three years after launch. Sample returns are required because the signs of life are so **difficult** to detect that we don't know how to do it with instruments that can be carried to Mars. We must look for them with sophisticated laboratory equipment on Earth.

ALH84001 - A Bearer of Signs of Life?

In 1984 an expedition to Antarctica, funded by the National Science Foundation, found a meteorite which was eventually brought to NASA's Johnson Space Center for **"curation"** (storage), It wasn't until 1993 that the meteorite was found to be probably from Mars - by far, at perhaps 4.5 billion years old, the oldest of the twelve meteorites now believed to have come from the red planet. The association between these **"SNC"** meteorites and Mars has been made by chemical and isotopic studies which link the meteorites with the findings of the Viking landers, and with each other, but not with the Moon or Earth,

The meteorite was believed to have been blasted off the surface of Mars by a giant meteor hit millions of years ago, and to have drifted in space until falling to Earth about 13,000 years ago. In 1993 a team of scientists began to use the most modem techniques to study ALH84001. They revealed their findings in August 1996. They believe that the combination of chemical and morphological evidence is a strong indicator that evidence of past Martian life exists in the meteorite. They have determined that the material they studied was deposited about **3.6** billion years ago, in water-filled cracks in the 4.5 billion year-old rock. Life on Earth is also believed to have started about 3.6 billion years ago, in warm water environments,

From the visible evidence of volcanoes and stream beds, ancient Mars had surface and subsurface reservoirs of warm water, similar to conditions under which life is thought to have developed on Earth. So if early Mars developed in a similar fashion to early Earth, it **is** reasonable to assume that life on the two planets might also have developed similarly.

On Earth, **life** developed in ancient rocks, evolved in surface water reservoirs (oceans and lakes), and is now present everywhere, On Mars **life** could have developed and evolved in a similar way, but would have had to "go underground" in some way to survive when Mars became cold and arid, It **is** possible that simple life still exists on Mars in subsurface lakes of **liquid** water beneath a **thick** layer of ice, or in still-warm reservoirs which might exist if Mars is volcanically active today.

Science Strategy for **Looking for Evidence of Martian Life**

The **first** step in the strategy of looking for life on Mars will be to analyze the existing SNC meteorites and to mount a search for more or them. The next step is to acquire fresh samples from Mars to analyze on Earth where the most powerful instrumentation and analysis techniques can be brought to bear.

A strategy of searching for life on Mars follows the evolutionary process: look for evidence of the beginnings of life in the most ancient parts of Mars, look for evidence of the evolution of life in ancient reservoirs of water, and then look for evidence of present life in current water reservoirs.

This strategy suggests that three types of sites should be explored:

1) The ancient highlands where it is believed that the **ALH84001** meteorite originated and where life might have originally formed 3,6 billion years ago in water-filled cracks in ancient rock,

2) Ancient lake beds or regions where water was collected for long periods, where life might have evolved,

3) Current reservoirs of water, particularly hydrothermal reservoirs of warm water (if they exist), where extant life might still survive,

The sites should be explored in this order because fossil life is more likely than extant life, and because - while we know whereto find ancient rocks and ancient lake beds -we do not know where current water reservoirs might be (or even if they exist).

The science strategy, therefore - simply stated - is **first** to look carefully from orbit to find areas suitable for more intensive study:

1. In ancient, cratered terrain where the impact of meteorites has thrown up material from deep underground onto the surface - probably the source of meteorites like **ALH84001** - where the search for evidence that life arose at all could be made.

2. In areas where evidence of ancient lakes exist - which might harbor microscopic fossils in their sediments.

3. In areas which are warmer than the surrounding areas - possibly indicating **near-** surface hydrothermal reservoirs like the hot springs of Yellowstone Park - or

4. In areas where liquid water still exists underground.

After these areas are identified from orbit, the strategy is to send surface missions - mobile, instrument carrying robots - to explore and analyze a few of the most promising areas located from orbit. It is relatively easy to **find** good sites in the ancient cratered highlands. It is even reasonably easy to locate ancient lake beds. (There are several sites already believed to be such and Mars Global Surveyor is expected to shed considerable light on these areas in 1998-99.) But it is **difficult** to locate either hot-spots or subsurface water from orbit, Therefore, the earliest landed missions should explore ancient terrains and lake beds with “rovers”, with more orbital data being gathered before targeting surface missions to search for extant life.

In addition to in-situ analysis the ancient-life-search rovers would acquire the best available samples in an area and store them for later collection and return to Earth. In this way the later sample return missions can select - from perhaps several caches - those most likely to contain evidence of **life.** Staging each sample return mission to follow one or more rover missions allows not only return of the best samples, but also may provide protection against the failure of a single rover mission.

Interspersed with the rover missions would be additional orbital missions with instruments designed to search for current reservoirs of water. These maybe infrared instruments to look for warm areas which could be subsurface hot springs. Alternatively or in addition, an orbiter could carry a radar for sub-surface sounding to look for liquid water deep underground. If near-surface warm water reservoirs are located, landed missions with relatively shallow drilling capability would be sent to access liquid water samples possibly containing life. If the reservoirs are deep, the capability must be developed to drill perhaps several kilometers to access the liquid water. This is another reason that the search for extant life would follow the search for ancient life.

The basic strategy, then, is to send orbiters, then rovers, then sample returns. At least one sample from each of the three types of area is needed to trace the possible evolution of life, and to have the best chance of finding some evidence of life if, indeed, it existed on Mars at all. Samples are necessary because current laboratory instrumentation required to do the kind of analysis that was done onALH84001 requires rooms full of a variety of large and sophisticated equipment. This kind of analysis cannot be done with small instruments capable of being carried to Mars, But small instruments carried by rovers can be used to identify the most likely samples to contain detectable signs of life.

Since the current Mars Exploration Program is carrying out the initial "Mars Life" strategy of investigating from orbit and then in-situ, no changes are necessary to missions through the 1998 launches. These include the Mars Global Surveyor orbiter, the Pathfinder lander, and the 1998 orbiter and lander.

Future Mission Implementation Strategy

The "Mars Life" implementation strategy would begin with the 2001 mission. A single, example implementation option has been selected for discussion in this paper. This option Is one of several developed by a team of engineers and scientists at JPL, Lockheed Martin Astronautics, and the Ames Research Center. Beginning in FY98, carrying out this strategy would require a substantial increase in funding over the current program,

As with the current strategy, two missions would be launched in early 2001, one a mineralogy and water mapping orbiter to aid in the selection of sample sites, and the other a rover to investigate the ancient highlands. A Science Definition Team under the leadership of Dr. Geoff Briggs of the Ames Research Center has been formed to define the science objectives of the 2001 missions, A possible payload for the orbiter would be the Gamma Ray Spectrometer payload to complete the Mars Observer investigations by mapping trapped water near the surface, and an instrument to make high spatial resolution (100 m) searches for key minerals or water. This might be, for example, a near-infrared imaging spectrometer or a thermal radiometer. Such sites would be ideal for searching for evidence of pastor present life, The orbiter would also provide communications and navigation support for its companion lander mission and for later lander missions until 2006.

The 2001 rover must be capable of much longer traverses than the '96 Sojourner rover and must carry instrumentation for determining the surface characteristics and mineralogy of the terrain that it encounters. This rover would also prove out the technology of a "robotic geologist", that is, it would be capable of selecting, examining, and possibly analyzing and even caching rock samples.

Next, in mid-2003, a single mission would be launched to land at a site selected with the data from the '96, '98, and 'O 1 missions with a rover to select and cache a sample to be returned. That rover would range tens of kilometers over half a year to a year of operation on the surface. A possible payload for the rover would be a panoramic imager, an ability to expose fresh rock surfaces and to break off rock pieces, a microscopic imager and near infrared spectrometer, and an organics detector. It also would be able to put samples in a container for eventual transfer to the sample return vehicle. As currently envisioned, the container would have a beacon to allow the sample return vehicle to **find it,** so that the rover does not have to be operable when the sample return gets there years later. It is possible that hardware redundancy in this mission may come in the form of two identical rovers on the single lander.

In late 2004 the sample return mission would be launched on a Delta 111 class vehicle to recover that cached sample in early 2007 and return it to Earth in mid 2008. That cached sample would be on the order of a kilogram including the container. The sample return mission would carry a small, short-range rover to fetch the cached sample, and would also have the capability to obtain a contingency sample that would be geologically significant.

In mid 2005 a small communications and navigation orbiter would be launched on a Taurus class vehicle to support lander missions outto2010.

In late 2006a second caching rover identical to the **first** would be sent to select and cache samples. In late 2009 a second sample return would be sent to collect that sample in mid2010 and return it in late 2012. This sample and the previous sample would have been targeted to address the ancient groundwater and ancient surface water sample objectives, either separately or, depending on serendipity, possibly each sample addressing both objectives.

In late 2011 an oasis mapping orbiter would be launched to find possible sites for extant life. A **strawman** payload would be a sounding radar for the detection of subsurface liquid water to considerable depth and, if not carried by the 2001 orbiter, a high spatial resolution thermal infrared **imager** to detect hot spots.

In late 2013a lander would be launched on a Delta **II** class vehicle with the capability of subsurface sample acquisition, caching, and preservation. This capability may not be mobile, but might simply drill straight down from the landing site where the orbital mapper indicated accessible liquid water. Also in late 2013 the third sample return mission would be launched on a slower trajectory to collect the subsurface sample in late 2014 and return it to Earth in mid 2016.

Again, the scenario just described is one path which could be followed. The actual path will vary depending on budget realities, scientific discoveries, and possible failures as the program proceeds.

Rovers and Robots in the Exploration of Mars

Obviously, rovers and other robotic systems are key to either the "Life, Climate and Resources" strategy of the current Mars Exploration Program, or to the more ambitious and focused "Search for Life" strategy. The **first** U.S. rover is Sojourner, (the *Mars* Pathfinder Microrover Flight Experiment). Sojourner is a NASA technology flight experiment which is on its way to Mars with the Mars Pathfinder lander for landing on Mars on July 4, 1997. After landing, Sojourner will be deployed from the lander and begin a nominal 7 sol (1 sol= 1 Martian day) mission to conduct a series of technology experiments, deploy an alpha-proton-x-ray spectrometer **(APXS)** on rocks and soil, and image the lander. This mission is conducted under the constraints of a once-per-sol opportunity for command and telemetry transmissions between the lander and Earth operators. As such, Sojourner must be capable of carrying out its mission with a form of supervised autonomous control, in which, for example, goal locations are commanded and the rover navigates and safely traverses to these locations. The successful conclusion of Sojourner's mission will not only result in a great increase in our knowledge of the composition and characteristics of the Martian surface, but will provide insight for the design of future rovers.

In January 1999 the U.S. will launch a lander with a robotic arm to land near the south pole, This lander will use the robot arm to trench into the soil with two primary objectives:

a. To place soil into a Thermal Evolved Gas Analyzer which will analyze the chemistry of the soil, emphasizing the detection of the form and isotopes of water, and

b. To view the walls of the trench to detect whether layering of dust and ice has occurred with the passage of the Martian seasons.

The lander will also use a stereo camera similar to Pathfinder's to image the surrounding terrain in stereo and several spectra, and will use a descent camera to image the area around the landing site as the lander descends on a parachute and landing rockets. In conjunction with the lander an orbiter will analyze the atmosphere and take medium-resolution images of the surface to study weather. This 1998 orbiter will complement the global surface mapping which will be conducted between March 1998 and 2000 by the Mars Global Surveyor mission.

In 2001, in addition to the U.S. rover there is an opportunity for a joint U.S.-Russian mission to land a Marsokhod (a fairly large, 6 wheeled rover). The current mission profile for this "Mars Together" mission is for the Russians to launch their rover separately from the U.S. launches, with the U.S. providing a communications relay for the Russian rover. There are opportunities for instrument exchange between the U.S. and Russian missions, as well as opportunities for other international participation In the missions.

Technology Development

As the Mars Exploration Program progresses the need for increased mobility and analytical capability to get sample diversity and to select more specific samples will require improvements in rover mobility, navigation, and sampling capability. To enable roving within the tight cost constraints of the program will require low mass, extreme power efficiency, and great resistance to low temperatures. Therefore, continuous advances in rover technology are required, as well as advances in technologies to support rover and sample return missions.

Current designs for sample return missions require launch vehicles somewhat larger and more expensive than the "Med-Lite" launchers of the Mars Surveyor Program, But the ability to use even these launchers requires "light weighting" of the sample return spacecraft, and this in turn requires technology development. The current NASA Telerobotics and Mars Exploration Technology programs are funding development of key technologies required for future Mars missions. However, much of the technology to carry out the program strategy is not currently capable of being developed in the needed time frame with the existing funding levels. Increased funding for technology development between FY98 and 2005 will be required to enable the strategy.

High priority new technology developments include the following.

Site Selection:

High spatial resolution remote sensing instruments, operating from orbit, will be needed to provide information on mineralogy and detect thermally active regions (if they exist).

Sample Selection

Robotic vehicles (rovers) are required which are robust all terrain vehicles, capable of traveling tens of kilometers and surviving more than a year on the Martian surface, but which are light enough to be carried to Mars by a Med-Lite class launch vehicle. Improvements are required in thermal protection, energy storage, telecommunications between **the** rover and orbiters, mechanisms, solar arrays, electronics, and power conversion, These rovers must carry instruments to **identify** desirable samples, and must be equipped with tools to prepare and place the selected samples into containers, These containers must be capable of protecting the samples intact, perhaps for several years, before they can be picked up by the sample return mission.

The in-situ science instruments themselves must be developed. Instruments are needed which can **identify** aqueous minerals in rocks (which might harbor signs of past or present life), determine relative ages of the samples, and search for organic materials. The instrument suites must have very low mass and power requirements in order to be supported by the rover.

The needed sample acquisition tools must be capable of preparing and manipulating samples for analysis and placement into containers. These tools must also be low mass and power and capable of working in concert with the instrument suites on the rover.

In order for the rover to navigate and communicate, low cost, communication relay and navigation support systems must be included on the orbiters,

Sample Return

High impulse propulsion systems are required for ascent from the Martian surface, The **efficiency** of the propulsion system and the mass of the other ascent vehicle elements determines the size and cost of the Earth launch vehicle, so very low mass spacecraft components and systems are also needed. High efficiency propulsion and low ascent vehicle mass will enable the use of **affordable,** medium sized launch vehicles which are expected to cost well under $ 100M, rather than vehicles costing two or three times as much.

In addition to being very low mass, the system must be able to survive for at least a number of days on the Martian surface. This means that advances are required in power and thermal control.

Technologies are needed which allow the sample return spacecraft to land with great accuracy, close to the samples which have been collected by the rover on a previous mission.

Sample packaging technologies which address back contamination prevention requirements are needed. That is, the sample containers must be capable of being completely sealed so that no Martian material can escape. They must be capable of being sterilized on the outside, and must not allow any escape of material even under very drastic conditions resulting from Earth entry failures.

Planetary Protection - For Both **Earth and Mars.**

Missions to Mars must be careful not to contaminate the surface with terrestrial organisms. Clear cleanliness standards exist for missions which will go to the surface, but **not** look for extant life. Mars Pathfinder in 1996 and Mars Surveyor 98, for instance, are being carefully cleaned. For missions which are intended to_ extant **life,** however, any Earth organisms at all are intolerable because one can't be sure that any "Martian" organisms found aren't passengers from Earth. Heat sterilization is currently believed to be necessary, but this adds a great deal of expense to a mission because of the impact of high heat on sensitive electronics and materials,

For sample return missions a very large issue in addition to the protection of Mars from Earth organisms is "back contamination". This is the necessity to make sure that no potentially dangerous Martian organisms are returned to Earth and released into our environment, A policy on back contamination is currently being developed by a committee of the National Academy of Sciences. Protection against back contamination is a large and unknown, lien against the cost of a sample return mission, A key element **will** be to "break the chain of contact", that is, to somehow make sure that no surface which has touched Mars touches the Earth, unless it's in a safe facility with adequate safeguards against the escape of organisms.

Rover Design

If Sojourner **is** successful there will be a wealth of information available in the summer of 1997 on the performance of a single rover design on the surface of Mars. This information can be made available to anybody wishing to focus their rover development activities on Mars exploration. The development of Sojourner has already demonstrated how **difficult** it is to build an autonomous vehicle capable of operation in an extremely remote, extremely hostile environment with extremely limited resources, The operation of Sojourner will tell us more about what works and what doesn't work. It will provide data for the designers of future Mars rovers to focus their efforts on the real problems inherent in the exploration of planetary surfaces.

A Challenge to the International Rover Community

This conference, which follows the Planetary Society's "Rover Expo" held in Washington, **D.C.** in 1992, provides an opportunity to demonstrate and compare different rover concepts. However, it will be important to marshal the skills of the world in developing and applying rover technologies if the ambitious program of Mars exploration described above is to be carried out within the required time frame and within a feasible budget. **I** challenge the participants in this conference to devise and build rovers which meet the challenges of the Mars Exploration Program.

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