Next Steps 17

Despite the astonishing progress to date, most of the major and fundamental questions regarding Mars remain essentially unanswered. We are in an excellent position, however, to take the next steps toward finding an answer. Currently, thousands of scientists across the world are pouring over the incredible amount of data being returned by the numerous space probes orbiting and on Mars. Unprecedented numbers of scientific papers and increasing frequent international conferences reveal the latest findings, and slowly but surely a comprehensive picture of the planet is taking shape. An entirely new generation of Mars scientists is currently emerging, armed with the hindsight and experience of those who came before, with brand new insights about the planet and with know-how on pursuing the next questions. The exploration of Mars is now one of the hottest topics in science. But the task ahead is truly enormous. It will take many more missions and many more years of sustained effort by the major science groups, universities, and national and international space agencies of the world before we can truly understand the planet's natural history and what it has to say about life.

New Motivations

While in the 1990s it was essential to identify fundamental questions about Mars and to devise an ingenious phased strategy to pursue them, several significant new factors now impact on how we should explore the Red Planet. Of course the phased strategy remains a central motivating factor: pursuing the global to the specific, past to present and geochemistry to biochemistry, in a phased manner, remains the cornerstone of our efforts. To date, orbital reconnaissance and geochemical lander missions have validated our initial conjectures on Mars' active past—the role of water, its broad connection with Earth, and that it may yet provide valuable insight into a planetary context for life—the results of our efforts demand that we continue with a phased strategy toward fully characterizing the planet.

K. Nolan, *Mars, A Cosmic Stepping Stone*,
DOI: 10.1007/978-0-387-49981-9_17, © Praxis Publishing, Ltd. 2008

The paradigm shift in our perception of the planet, brought about by current exploration (that of the complexity of Mars), must also be considered. Prior to Mars Global Surveyor, few could have envisaged the true complexity of Mars' landscape and history; and now we must factor this into our continuing program. We cannot yet declare that we have surveyed the planet adequately. The vast landscape that is the geological legacy of Mars remains largely elusive—at times even paradoxical—and we have much more to do. Literally hundreds of sites of potential biological interest have now been identified that demand Phase 3 biological landers and Phase 4 sample return missions; but the uncharted complexities of the planet at large also demand that ever improved orbital-, aerial-, and lander-based geological and geochemical reconnaissance must also continue.

Our explorations have also thrown up surprises regarding Mars' current behavior. The realization of the extent of (a) quasi-periodic climate change and the resulting discoveries of glaciation on the flanks of the great volcanoes, (b) geologically recent tectonic and water activity at Cerberus Fossae, (c) methane in the atmosphere, and (d) permafrost in the high latitude and polar regions are all relevant to our pursuit of the question of life on Mars. But they are also largely unexpected findings. Clearly Mars today is a dynamic world in ways that were not expected, and we must also make new efforts to understand such dynamism. The initial motivations behind our phased strategy were primarily about understanding Mars' past, but now we realize that there is a great deal to learn about its current state and behavior. Here again, new and innovative orbital and lander reconnaissance will be required.

Despite the new demands on the Mars program, our phased approach is perfectly suited to the task. None of the probes sent to the planet since Pathfinder has been ill-conceived, ill-timed, or scientifically inappropriate. All have worked and complemented one another very well, providing an ever-maturing understanding of the planet. And with time and opportunity to respond to current findings, the next generation of orbiters and landers will be appropriately designed, built, and equipped to accept the new challenges that Mars now presents—and there need be no conflict with our original aspirations. If the search for origins is important, then so is Mars; and this is not lost on the program designers, engineers, and planetary scientists currently involved with Mars exploration.

The success of the Mars program to date has drawn widespread commendation both from within and beyond the scientific community. Despite the hiccups and losses along the way, the overall program has worked extremely well, delivering spectacular results, with each probe outperforming its original expectations many times over. Also, the phased approach to the program has even provided a viable way forward for other space programs that are arguably stuck in a rut or suffering from a lack of direction. The current Mars program is the most focused and successful endeavor since the Apollo missions to the Moon and the Voyager reconnaissance of the outer Solar System. And where programs such as the Space Shuttle and the International Space Station are technically unprecedented, they have essentially remained exercises in the development of enabling technologies, but whose purpose has not yet been fully realized. In contrast, this has not been the case with the Mars program. From the outset it has been driven by well-defined and realistic goals, with the phased strategy progressing in a stepwise fashion toward their realization. All of these factors have led to a heightened political and social interest in Mars exploration that did not exist at the beginning of the program. An ownership of (and expectation for) Mars exploration is now emerging, not only by the science community but now also by politicians and the general public.

A renewed political interest in space exploration now exists within the USA, the EU, Japan, China, and India, with Mars as a high priority for many. The rewards are substantial—national achievement and standing, technical innovation driving science, education and the economy, as well as international acclaim and supremacy. And while the USA currently leads the way, the others are rapidly gaining ground. In this pursuit, Mars beckons. The success of the current phased strategy of robotic exploration has provided a template on how to safely and cost effectively pursue far-reaching space exploration. The possibility of exploring Mars, whether by robot or by human, is now real and many of the space-faring nations are interested. Already the USA and the other space-faring nations have politically declared a desire to send people to Mars in and around 2033; and whether this is feasible, such formally declared political will is unprecedented. Never before had any space-faring nation proposed sending people to Mars. Indeed the US government and NASA have previously been careful to draw the line at such a declaration, but this no longer applies.

As has already been discussed, major efforts are underway toward this end; with ESA's Aurora program now politically ratified by EU participating states and George Bush's Vision for Space Exploration (VSE) already impacting on budget allocation to future space exploration. The politically declared interest in Mars is real and is probably here to stay; and while it may be contentious and difficult to implement, never before has such a long-term and permanent interest in Mars been expressed. Whether we eventually send people to Mars or not, the intervening efforts, both robotic and human, will all be affected. Roadmaps, programs, missions, timetables, and budgets must all adapt—and are currently doing so—to accommodate the possibility of a human mission to Mars. And so the robotic phased strategy for Mars exploration must now function within a broader framework. There will be setbacks, as in the 2007 NASA budget announcements, that radically affects the time line for some upcoming robotic missions to Mars, but the nature of the phased program means that even where delays occur because of shifting priorities, we will always be able to continue precisely from where we left off, supported by the significant work already carried out.

Also emerging is a broader sociological and cultural dimension to Mars exploration. Initiated by the unprecedented interest in the Pathfinder mission there has not been such a healthy awareness of and interest in space exploration since the Voyagers. This was significantly augmented by the emergence of the World Wide Web, where, for the first time, we could all share in the spectacular findings on Mars in near-real time from our homes and offices. As in so many other facets to the modern world, the anarchy that is the World Wide Web has to some extent democratized the former privilege of space exploration, and an appetite for it has emerged. Such has been the success of Mars exploration—and of NASA's and JPL's desire and ability to disseminate their finding almost live to hundreds of millions of people—that there is now an emerging acceptance, if not expectation, for robotic exploration of Mars in particular. Today, such exploration is taken for granted, perhaps too much so, but it is more than tinged with an unspoken consensus that the price/performance of robotic exploration is now pitched correctly and should continue. This is something to which JPL in particular can readily respond. With their abounding successes to date, JPL can now respond almost as a matter of course in building ever more sophisticated Mars exploration robots. Such exploration has become accepted as a valid pursuit for the long term.

Current political and cultural interest now sets Mars in a broader context. The path to Mars is no longer purely scientific; it will increasingly be defined by political and sociological interests. Mars is rooted in modern life as never before, and with the successes to date and know-how at our disposal, pursuing such a broad agenda for Mars is not a problem. This is what sets us apart from all previous efforts to reach Mars. We know the full extent and scale of the challenges ahead, and can respond by implementing a phased strategy to overcome them. Our strategy is an *enabling strategy*, because it does not have a singular and troublesome end point of pending potential failure. We'll send people to Mars when it is safe to do so, is technically possible and is financially feasible, and in the meantime will build toward that goal and learn along the way. We have developed a sense for Mars exploration and it will always be a part of future society.

Objectives

Our objectives for Mars exploration are now many and varied. The path from robotic exploration to a human mission is long and tough but can, none the less, be capably pursued via the phased strategy now implemented through the Vision for Space Exploration and Aurora programs. For the next decade and a half, three particular objectives present themselves: to contine the robotic exploration of Mars with a view to achieving defining answers about its natural history; to conduct technology test bed missions with a view to a long-term human presence in space; and to initiate a new program of deep space human exploration to the Moon, Mars, and beyond.

Phase 1 and Phase 2 Robotic Explorations

Concerning the robotic exploration of Mars, we will continue with Phase 1 orbital reconnaissance and Phase 2 geochemical lander missions for some time to come. Here we wish to find defining answers about the exact nature of Mars' ancient climate, the extent of water activity and the types of chemistry occurring during the Noachian period in particular. We must also determine the evolution of the planet and precisely how and when it collapsed to its current state of relative dormancy.

Also of importance is the character of the planet today. Here we need to determine any prevailing seasonal and annular weather patterns and discover how global dust storms arise, as well as the nature of quasi-periodic climate change occurring over thousands of years. We must determine the internal structure of the planet and whether tectonic and volcanic activity persists, and if so their impact on the release of water and other volatiles. We must also determine the current story of water—whether underground ice and aquifers exist and, if so, their potential both as habitats for Martian life and as a resource for future human missions.

All of this can be achieved through various means. For example, many of the current reconnaissance orbiters can survive into the next decade, with their missions adjusted and even in some cases improved through software upgrades or changes in modes of operation. For example, Odyssey can theoretically continue until 2014 and Mars Express until 2010; and although Mars Global Surveyor has now failed, an innovative technique developed by Mike Malin and Ken Edgett in 2003 called "compensated pitch and roll targeted observation" or cPROTO improved MGS's MOC camera to 0.5-meter pixel resolution, demonstrating that, even in operation, significant space mission enhancement can be successfully made. Furthermore, even with the existing datasets, we are set to tackle many new and outstanding questions about Mars through sustained analysis in the coming years. As in the case of the Viking orbital dataset, painstaking analysis of the vast quantities of data already available today are likely to provide significant new finds.

New and upcoming orbital reconnaissance and geochemical lander missions will also provide valuable new data. The Mars Reconnaissance Orbiter is now the benchmark against which all future orbital missions must be measured. It routinely photographs the surface of Mars at a resolution of less than 1 meter—in many cases sufficient to provide definitive answers regarding the nature of sedimentary layering and other small-scale geological features.

Finally, NASA's Phoenix (2008) and Mars Science Laboratory (2009), Russia's Phobos-Grunt sample return mission to Phobos (2009), and ESA's ExoMars (2013) and proposed sample return mission to the surface of Mars (2016) will of course also provide extensive new insight into the geological, geochemical, and chemical nature of Mars, past and present.

Phase 3 and Phase 4 Robotic Explorations

We are also now ready to proceed to Phase 3 biological lander and Phase 4 sample return missions to Mars; and already the key missions toward this end (mentioned above) are in the development or the planning phase. Evidence from existing reconnaissance points to the possibility of prebiotic chemistry and even microbial life arising on Mars billions of years ago, as well as to the possibility of life surviving today in niche habitats or in a dormant state until climatic conditions become more favorable. Many ancient sites of past water and hydrothermal activity have been identified where prebiotic chemistry and microbial life may have arisen, and where fossilized evidence of that activity may persist. Meridiani Planum, Valles Marineris, Syrtis Major, Arabia Terra, Nili Fossae, and Marwth Vallis are but a few of the many sites now attracting interest.

Furthermore, orbital reconnaissance also points to the polar and polar-layered regions as well as the possible frozen sea south of Elysium, among many other locations, as potential habitats today where biomarkers and even microbial life might exist. To this end, the landers mentioned above—Phoenix, the Mars Science Laboratory, and ExoMars—represent a brand new phase set on exploring the biological potential on Mars. Each will be equipped with instruments capable of determining the surface chemistry, the presence and origin of organic materials as well as searches for fossil evidence of past life and biomarkers associated with current or dormant life. Unlike the Viking missions, these three landers will be sent to sites deemed likely to provide the best scientific return, with their instruments specifically tailored to their selected environment. Also, in the planning phase by ESA (and with strong interest by NASA though its 2007 budgetary commitments make such a mission less likely for the USA) is a sample return mission to the surface of Mars, to take place around 2016. Given the intriguing picture of Mars that is emerging, considering the great unknowns that still persist, the scientific community resolutely recognizes the need for an imminent sample return mission. Such a mission would return samples from Mars to Earth, significantly accelerating our ability to decipher the planet's long history and the quest for signs of life activity. The technical and logistical challenges presented by such a mission represent an excellent opportunity and necessary precursor step toward a human mission.

Technology Testbed Missions

Each and every mission launched into space represents an experiment in technical innovation. From the aerobraking capability of MGS to the airbag technology used to set Pathfinder, Spirit, and Opportunity onto the surface—and from the TES infrared mineralogical detector on board MGS to its derived mini-TES detectors on Spirit and Opportunity—each has not only played a vital part in the success of its own mission but has also contributed to enabling ever more sophisticated and innovative subsequent missions.

Overall, enormous strides forward have been taken since the 1990s, to a point where the robotic exploration of Mars is almost taken for granted. But if we are to fulfill the phased strategy of VSE and Aurora and send people to Mars within three decades, we must become equally apt at devising systems capable of delivering people safely to Mars, sustaining them on the surface and returning them to Earth perhaps three years after launch. We are so far from such a capability that a significant and relentless effort in technological innovation is required from this moment on, across a myriad of areas such as rocketry, habitation modules and vehicles, EDL systems, power and propulsion, guidance and navigation systems, communications, computing, life-support, and rover vehicles, among many others—all to be developed and capable of performing for many years without degradation.

Currently, several different approaches to achieving such capability are envisaged. First, each new mission to Mars is required to extend current science and so will, by definition, require technical innovation relevant to the future of the program. Second, part of the remit of each mission must test new technology necessary for future missions. Here, the technology being tested may not necessarily be central to the current mission, but will be vital to future missions. Third, specific testbed missions will be executed, whose role is purely to test new technology.

To this end, NASA is already actively engaging new technological innovations in all impending Mars missions. Furthermore, a new category of *scout missions*, of which Phoenix is the first (and which can be pitched for by other organizations outside JPL), will inspire technical innovation within institutions across the USA. The Mars Reconnaissance Orbiter, for example, will not only bring scientific reconnaissance to a new level of sophistication but will also test new modes of guidance, navigation, and low-powered communications. The Phoenix lander will rely upon a new thruster-based controlled landing system to touch down on the surface and will also use a new robotic arm and scoop mechanism for delivering soil samples to its various onboard experiments. The Mars Science Laboratory (MSL) will test an entire suite of new technologies: precision landing, long-range roving, self-guidance, and possibly radio-isotope nuclear power. Other NASA scout missions will also test a range of technologies from precision landing to orbital telecommunications.

ESA is following in like fashion, where its flagship missions ExoMars and the proposed Mars Sample Return Mission will by default require significant technical innovation and where its smaller arrow class missions will function only to test new technology. The two arrow class missions—an Earth re-entry capsule and an atmospheric friction-based orbital entry system—are already planned and will specifically test the systems needed by ExoMars and Sample Return Mission. ExoMars itself, as with the MSL, will test long-range roving, autonomous navigation, and guidance and drilling, while the Sample Return Mission will require a range of new technologies including the use of no less than five spacecraft over two missions—a Mars Ascent Vehicle (MAV) to launch the samples from the surface of Mars, Mars-orbital docking maneuvers, and return vehicles capable of traveling from Mars to Earth—all unprecedented and directly applicable to an eventual human mission.

Future Missions

As enthralling as current Mars exploration may be, the future years promise to take our engagement with the planet to even greater heights. With aspirations of acquiring defining answers about the planet and of laying the foundations for sustained human exploration, the missions pursued in the next decade will be of critical importance.

Phoenix

Phoenix is NASA's first scout mission to Mars and the first Phase 3 exobiological lander of the current era. As a scout mission, Phoenix is designed and operated by the University of Arizona's Lunar and Planetary

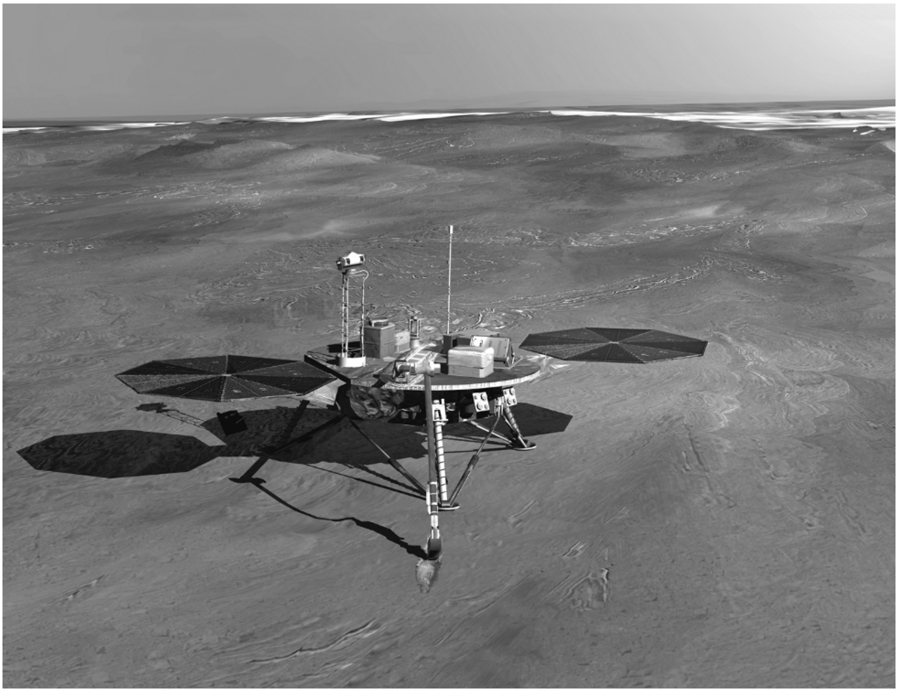

Figure 101: Artist's rendition of the Phoenix lander on the arctic plains of Mars just as it begins to dig a trench through the soil. The polar water-ice cap is shown in the far distance. [Credit: NASA/JPL/ Corby Waste]

Laboratory, having been selected in an external competition aimed at triggering innovation across the USA. Landing on Mars' frozen arctic northern lowlands, Phoenix is the first space probe to be sent to a location that was selected on the basis of the possible presence of water (Figure 101).

Launched in August 2007 and successfully landed on Mars on May 25, 2008, Phoenix is a fixed lander, using a robotic arm to dig into the icy soil and deliver samples to a suite of onboard science instruments and experiments. The primary aims of the mission are to study the history of water in the region and to examine the suitability of the soil for life. In particular, Phoenix will provide ground-truth information for Odyssey's GRS instrument which has already identified areas of up to 50% water within the soils of the northern arctic. Such ground-truth will allow for a more accurate interpretation of all GRS data, leading to a better understanding of the natural history of water across the entire region. By specifically analyzing the soil, Phoenix will also provide valuable insight into climate change from as recently as 100,000 years ago.

Although Phoenix will not specifically look for life, it will be able to survey the suitability of its landing site as a potential habitat and, in particular, determine ways in which it might act as a habitat. Using its onboard TEGA Furnace in tandem with a mass spectrometer, samples of soil will be heated to 1,000°C from which the presence of water, other volatile materials and life-giving elements such as hydrogen, carbon, nitrogen, and phosphorus can be identified. Furthermore, with a sensitivity of 1ppb (part per billion), any organic materials within a sample will be easily detected, perhaps revealing the presence of life or of biological by-products. Another onboard instrument called MECA will conduct wet-chemistry experiments, determining both the acidity and salinity of the soil and revealing potential sources of chemical metabolic energy. By dissolving soil samples in water, MECA will also be able to detect the presence of a range of chloride, bromide, and sulfate salts, as well as the presence of oxygen and carbon dioxide. Finally, with an optical microscope accurate to 4 microns and an atomic-force microscope accurate to an incredible 10 nanometers, any hydrous or clay materials in the soil will be directly detectable, revealing the history of water activity at the landing site. With stereo-imaging and meteorology detectors, Phoenix will provide significant insights into the history and current activity of water at its landing site and, for the entire northern arctic region, reveal vital details on quasi-periodic climate change, determine the suitability of the site as a possible habitat, and detect any organic materials present. Indeed, within four weeks of having landed, Phoenix provided unequivocal evidence of water-ice residing at the surface, just below a thin layer of dust. The discovery, of historic importance, validates our search for water and life-related activity on Mars and heralds a new era of Mars exploration, in which Phoenix's findings will play a major role.

Mars Science Laboratory

The enigmatic Mars Science Laboratory (MSL) will be launched to Mars in 2009, arriving on the surface in 2010. Weighing in at four times that of Spirit or Opportunity, the MSL exobiological rover is designed to travel more than 10 kilometers from its landing site during its 668-day (almost a Martian year) primary mission (Figure 102). MSL represents another significant step forward in Mars exploration and an unprecedented opportunity to search for life on that planet.

On arrival, MSL will use a guided precision system to land closer to its intended target than any previous rover. The target chosen will be one deemed to be of greatest biological potential. Although MSL will not bring metabolic and growth experiments similar to those on board Viking, it will carry the most sophisticated science package ever sent to another planet, capable of identifying a great number of life signs, past and present. MSL's science goals include:

Figure 102: Artist's impression of NASA/JPL Mars Science Laboratory (MSL). MSL will be larger than the MER rovers, be able to travel over 10 kilometers from its landing site, and look for evidence of biology on Mars. [Credit: NASA/JPL]

- Characterize the geology of an entire region on Mars to the microscopic level.
- Analyze the mineralogical, chemical, and isotopic processes shaping rocks in the region.
- Access the long-term evolution of the planet.
- Investigate the cycling of water and carbon dioxide.
- Investigate past processes in the region relevant to past prebiotic chemistry and life.
- Identify and analyze fixtures possibly harboring evidence of life, including the possible identification of any of thousands of different organic molecules including microfossils.
- Determine the toxicity and radiation hazards for humans on Mars.

To accomplish this, MSL will carry a science package including a number of exquisite imagers: a panoramic stereo camera, a contact microscope, X-ray and neutron detectors of higher specification than those on the MERs, as well as new and revolutionary experiments such as ChemCam (a laser-fired chemical analyzer), SAM (a gas chromatography mass spectrometer (GCMS)), CheMin (an X-ray fluorescence spectrometer), and DAN (a neutron detector) capable of identifying the presence and structure of subsurface water to one-tenth of 1%. Also on board are two instruments—a

Radiation Assessment Detector (RAD) that will measure cosmic radiation levels on the ground, and a Spanish-built Rover Environmental Monitoring Station (REMS), capable of monitoring ultraviolet levels, air temperature, barometric pressure, humidity, and wind speeds and directions. Using the chemical detectors in combination with REMS and RAD, the Mars Science Laboratory will be able to determine for the first time the toxic and radiation hazards likely to impact upon a human mission.

MSL will perform three fundamental types of analysis. First, it will scoop soil and rock samples and bring them on board for analysis by SAM, ChemCam, and CheMin. Second, it will carry out contact investigations using its onboard imagers, microscopes, and spectrometers. Finally, it will conduct remote-sensing analysis (without physical contact) using its imagers, radiation, and meteorological instruments.

It will thoroughly investigate its landing region for evidence of past and present water and life-related activity, determine past "water activity" levels, and search for thousands of organic molecular types that may constitute biomarkers of past or present life. It will also look for rocks and clays perhaps retaining evidence of prebiotic chemistry or microfossils, as well as perform morphological, mineralogical, chemical, and organic chemistry experiments to identify the precise origin and nature of any such evidence. The results from MSL will impact significantly upon current ideas about Mars, providing significant new insights into the nature of the planet and, in particular, heralding a new era in astrobiology field studies.

ExoMars

Europe will launch it first Aurora flagship mission in 2011. Called ExoMars, this exobiological rover will set down on Mars in 2013 using an air-bag and parachute system, at which time MSL may well be still operational (Figure 103). Despite being ESA's first rover, the ExoMar science package—appropriately titled *Pasteur*, because it will look for evidence of life—already has a long pedigree. Many of Pasteur's instruments are derived directly from Beagle 2 and the French Net-Lander network of Mars landers. Despite the fact that none of the instruments has been used on Mars, they have none the less had an extraordinarily long development and test period, ensuring their optimal operation.

ExoMars will not only complement but also greatly extend the biological analyses of MSL. Its science goals include: the characterization of the site geology, mineralogical, and chemical analyses of rocks, soil, sand, and dust; the detection and characterization of any organics present; and the identification of chemical and biological biomarkers. Similar to MSL, ExoMars will have a number of sophisticated cameras, microscopes, and an

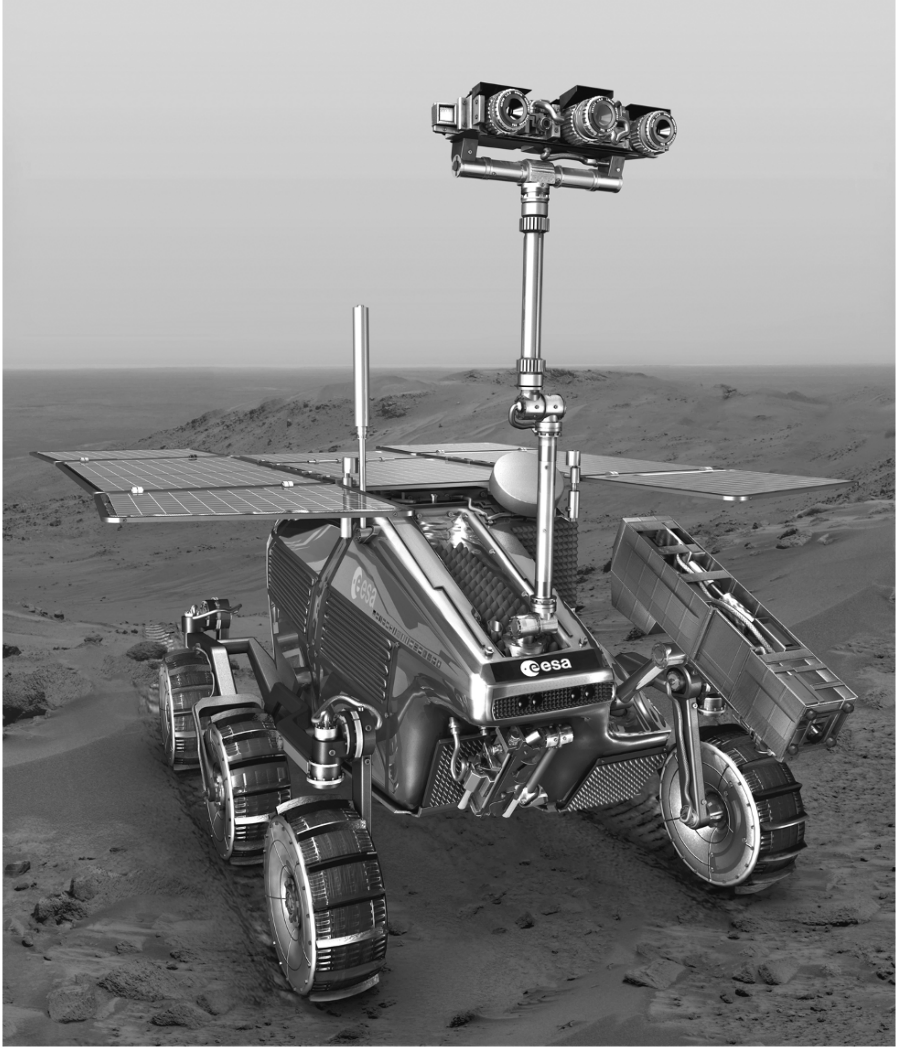

Figure 103: The ExoMars rover will be ESA's field biologist on Mars. It aims to characterize the biological environment on Mars in preparation for robotic missions and then human exploration. [Credit: ESA]

APXS for surveying the site geology as well as mineralogical and morphological studies of surface materials. A number of other features unique to ExoMars, however, will make it the most sophisticated biological lander ever sent to Mars. With two onboard drills, ExoMars can extract samples as deep as 2 meters below the surface, thereby accessing soil that has not been affected by harmful radiation or the oxidizing surface. Samples will be delivered to the onboard Pasteur mini-laboratory for analysis by a number of instruments and experiments, and by this capability Pasteur will excel like no other lander in history. Included within Pasteur are a GCMS capable of detecting organics to part per billion levels, a separate GCMS with a unique *biomarker microchip* for detecting amino acids and aromatic hydrocarbons, and yet another and separate biomarker microchip to allow for the identification of a range of chemical and biological biomarkers from past, dormant, or present life. Through ExoMars, we are confident that if evidence of past or present life exists at the landing site, ExoMars will find it.

Aerobots

Although they have not yet been scheduled, aerial robots or *Aerobots* will be sent to Mars at some time in the next decade. ESA has already put out a call for designs of such craft from students across the ESA nations, with the top 25 being considered for further development. Extensive work in both light aircraft and balloons for Mars has also been conducted by The Planetary Society and NASA.

The advantage of Aerobots, whether aircraft or balloons, is that they can carry out aerial reconnaissance work over large regions of Mars potentially to hundreds of times the resolution of an orbiter. Such a unique perspective could deliver spectacular views of the landscape and provide extremely high resolution analyses of more of the Martian surface than is possible from orbit. Aerobots will be critical to the identification of resources and in providing detailed landscape surveys for pending or already occurring robotic rover and human missions.

With an atmosphere less than 1% as dense as Earth's, aerial craft are extremely difficult to design for Mars. Given current materials, a light aircraft would have to be dropped into the atmosphere from, say, a descending lander, where it might glide for an hour or so. Even in that time, however, the glider (or gliders) could provide significant image and mineralogical data of a vast swath of Mars' surface in the vicinity of the lander, thus hugely enhancing its mission (Figure 104).

Using balloons, there are two viable options. First, an Ultra Duration Balloon (ULDB) could be dropped from an entering lander, where it would quickly inflate with helium. A second type of balloon is a Solar Montgolfier Balloon (named after the French brothers Joseph and Jacques-Ètienne Montgolfier who pioneered ballooning), which is open to the Martian atmosphere and where buoyancy is achieved by solar-powered heating of the air within the balloon. With comprehensive payloads on board, balloons might be constructed with a buoyancy that varies between day and night. With the aid of a long tether, the balloons may never descend fully to the surface and remain afloat for long periods of time. Instruments attached to

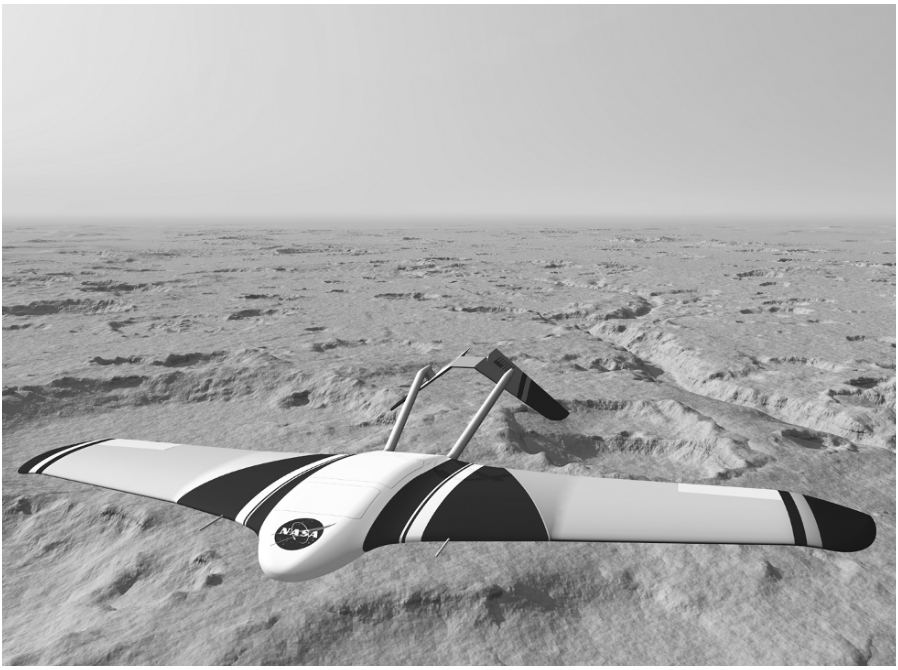

Figure 104: Artist's impression of a light aircraft gliding through the atmosphere of Mars. [Credit: NASA/John Frassanito and Associates]

the base of the tether might even be able to extract ground samples at the current location for analyses.

Mars Sample Return

Despite the ferocity with which we are pursuing robotic exploration on Mars, it may take decades to attain a full picture of the nature of Mars, past and present. In this respect, any means at our disposal that maximizes our ability to understand its nature must be seriously considered, and engaged where possible. As sophisticated as robotic explorers may be, they are arguably too limited to fulfill our aspirations for Mars. First, they are a mode of exploration in which those involved are one step removed from the actual process of exploration. Also, for the foreseeable future, robots will remain more cumbersome and less flexible than humans in field operations. In the case of a stationary lander, for example, there is nothing that can be done if a point of interest is simply beyond its reach. Rovers also have limits to their maneuverability in terms of the roughness of the terrain and the steepness of slopes that can be engaged. Even a change in direction can be a major ordeal, taking hours, if not days, to fully complete. There are also severe limitations to the sophistication of the instruments and experiments on board robotic rovers in particular, mainly due to weight constraints. Even some of the most sophisticated equipment to be sent to the surface of Mars in the coming decade will not be the equal of its Earth-based laboratory counterpart.

Furthermore, where the capabilities of onboard equipment are sufficient for the task, the nature of the beast is that answers are rarely 100% conclusive. They usually lead to more questions and a requirement for further investigation, and in this respect robots are of little use. In the case of Opportunity, for example, where it has already delivered spectacular results regarding past geochemical and water activity in the region, it is utterly incapable of conducting the types of exobiological investigations intended for MSL and ExoMars. In reality, unless it is selected as a target for a future mission, it will be decades, or longer, before we return to Meridiani Planum to conduct such investigations. Also, imagine the situation if Phoenix, MSL or ExoMars were to detect the presence of life activity. Will a single rover at that location fully satisfy the flood of new questions that will follow about the origin, nature, evolution and full extent of such life across that entire region and, indeed, the planet at large? Even in less dramatic circumstances, we are already finding a proliferation of fascinating environmental scenarios that prompt new questions, many of which we are powerless to follow up.

Using robots alone, every new question about Mars requires a new mission, and eventually this becomes too cumbersome and ineffective. Our use of robots for initial surveys is entirely appropriate and to date they have been (apart from the study of the SNC meteorites) our only means of conducting analyses on Martian materials. But already we are finding that Mars is so complex and our questions are so sophisticated that other means of examining Martian materials is becoming an imperative. For these reasons we envisage enhancing how science is done on Mars by two other methods: returning samples from Mars to Earth and via human missions to Mars.

The Mars sample return method would probably involve two simultaneous robotic missions in which the first collects rock, soil, sand, dust, and air samples and the second returns them to Earth. Having available samples from a known location on Mars whose regional context is also known would be hugely significant. We could apply the full weight of the best analytical techniques available, which are perhaps decades ahead of anything we can currently send to Mars. The returned samples could also be shared among many of the leading institutions and experts across the world, providing quicker answers and better insight. Newly arising questions could be immediately followed up, even if they require different or new analytical techniques. Also, as technological advancement provides better analysis tools and techniques than we have today, new insights into Mars could be gleaned from such samples.

Implementation

Currently, a sample return mission is planned for about 2016. The European Space Agency has already declared that their second Flagship mission will be a sample return mission. While NASA has also expressed a desire to conduct a sample return mission at the earliest possible moment—even as early as 2013—recent budget reallocations (to allow completion of the James E. Webb Space Telescope, for example), and the return of people to the Moon by 2020 have affected some missions of the Mars robotic program, including a Mars sample return mission. Despite this setback, NASA remains committed in the long run to a sample return mission, but with no specified date. Such has been the outrage expressed by the space science community at the shelving of such a crucial mission (especially in view of ongoing findings that increase the possibility that Mars may have supported life) that it is difficult to see how NASA's program for Mars can remain sustainable (and competitive). The most likely scenario, therefore, is for a single international sample return mission to take place toward the end of the next decade.

How would such a mission occur? There are several possible implementations, but among the most likely is a two-mission strategy. Here, the first mission travels to the surface of Mars, where a lander and/or robot gathers samples of many types of rock, drilled underground soil, surface soil (Figure 105), sand, and dust, as well as air samples collected at various times of the day, and, if the lander is there for a long enough period, at various times during the Martian year. The samples are then placed into a sealed capsule and transferred to a Mars Ascent Vehicle (MAV) which blasts off the surface into Mars orbit (Figure 106). The MAV may remain in orbit or it may put the capsule into orbit for future collection. A second space probe subsequently travels to Mars, collects the samples in orbit, and returns to Earth. Alternatively, the second vehicle might dock with the MAV to collect the samples. However such a mission is conducted, if successful it will be a milestone in space exploration. Not only will the returned samples be of historic importance, but the mission itself would have successfully demonstrated all stages of the journey for a human mission, providing a significant technical boost to the possibility of such a mission taking place.

Containment

Sample containment is one of the most contentious issues regarding a sample return mission. This arises because of the nature of our search for evidence of life and, in particular, *microbial* life. Hence, if we are serious about the possibility of life on Mars, we need to be even more serious in

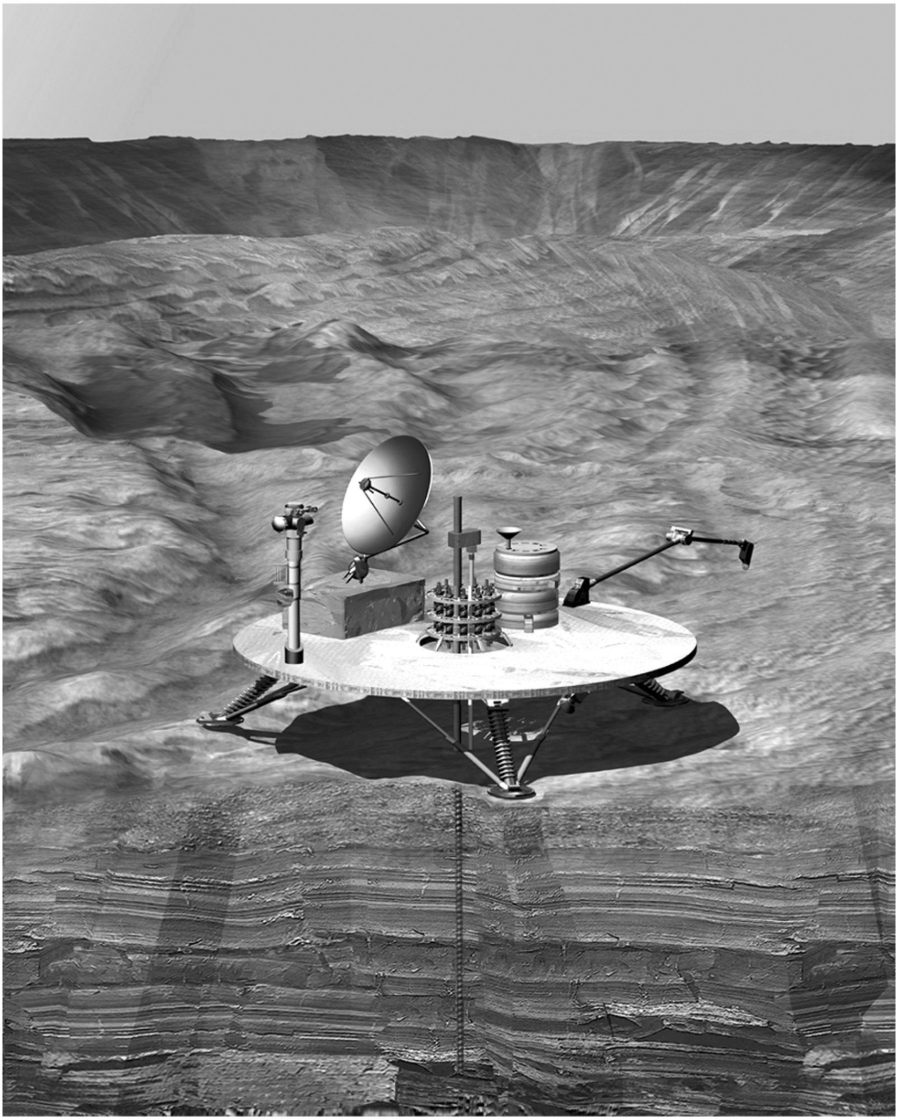

Figure 105: Artist's impression of a deep drill lander searching for evidence of life, past or present on Mars. It is likely that such a mission will take place in the next decade. [Credit: NASA/JPL]

evaluating and dealing with the risk to Earth's biosphere that is posed by the return of such samples.

There are those who argue that even if microbial life is found to exist on Mars and is present in returned samples, its impact would be essentially zero even if released to the general environment. Because the life-forms are from

Figure 106: Artist's impression of the launch of a Mars Ascent Vehicle (MAV), bringing samples into Mars orbit where they will be collected and returned to Earth. It is likely that such a mission will take place in the latter half of the next decade. [Credit: NASA/JPL]

Mars, they argue, they will bare no significant commonality to life on Earth. Toxicity aside, there could be no meaningful interaction between Martian and Earthly biology constituting a virulent or pathogenic threat. They argue further that there could be no meaningful competition between Martian biology within Earth ecosystems—and with the natural advantages available, Earth life-forms in their natural environments would win any competition for resources. Finally, they argue, even in the unlikely event of meaningful biological interaction taking place, it must already have occurred because we know that about 500 kilograms of Martian material fall to Earth every year, having been blasted into space by comet and asteroid impacts.

Those opposed to such arguments point out that we are still often unclear on the details of how terrestrial microorganisms adapt and evolve. And we already know of many microorganisms that have evolved in very short periods of time; for example, *Deinococcus radiodurans*, as mentioned on page 27, developed the capacity within only a matter of years to withstand otherwise lethal doses of nuclear radiation. And so we cannot say with certainty what the pathogenic or environmental competitive capabilities of Martian microbes might be. Furthermore, even if there was scientific certainty regarding the safety of such microbial life, would it be reasonable to ask the world community to accept such a recommendation of safety? Should the World Health Organization and national and international agricultural agencies accept such complacency? Would it not be reckless and ethically dubious if Martian samples were not treated with the greatest caution possible, to ensure maximum protection for our planet?

The chance of life having arisen on Mars is slim. The chance of life surviving through to the present is also slim and the chances of microbes living within returned samples extracted from close to the Martian surface are even more so. None the less, the worst case scenario—where living microbes released to the open environment reek havoc with some part of Earth's biosphere—cannot be completely ignored and therefore constitutes a significant risk and a requirement for extreme measures in containment.

In dealing with containment, leading agencies are developing policies and systems that are appropriate to the task. It might be a requirement, for example, that before landing on Earth, the samples will be sterilized, or even burnt. Although they will then be mostly destroyed, we may simply have to live with what we can determine about Martian biology from such sterilized or burnt remains of the sample—still of significant scientific value—until subsequent technological advances and return missions build sufficient confidence in returning pristine samples to Earth. Or perhaps they might be returned to a lunar outpost or an orbiting space station. There is no doubt that we are capable of engineering a containment system that can ensure the safe return of Martian samples to Earth. But the question is not simply one of engineering, it is also about public acceptability and world responsibility. Irrespective of the debate, the prospect of returning Martian samples to Earth will demand extreme measures in containment, and this is already being addressed by the appropriate world bodies, as we will see in detail in Chapter 19.