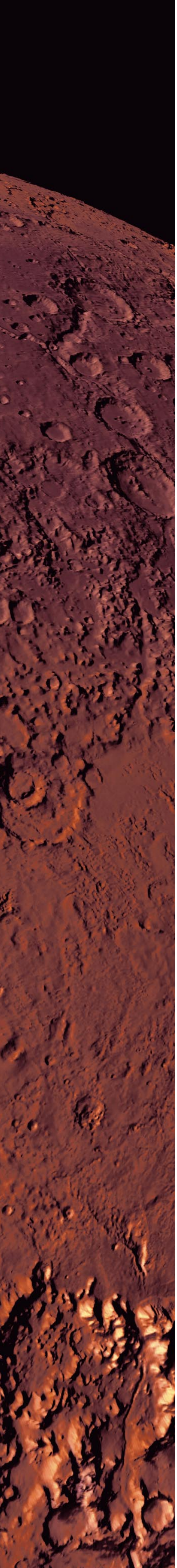

Mars exploration

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An international flotilla of spacecraft are to be sent to Mars over the next decade in an effort to understand the planet's geology and climate history, and to determine whether some form of life ever started there. At least two spacecraft will be sent at each launch opportunity, and at times up to four spacecraft may be operating simultaneously at the planet.

The exploration of Mars is an international endeavour involving many nations. The United States has recently reaffirmed its long-term commitment to Mars exploration, the European Space Agency is set to launch several spacecraft to the planet in the next few years, Japan has a spacecraft (Nozomi) *en route*, and other countries are making substantial commitments to the effort. This global interest stems from a variety of causes. Mars is the most Earth-like of the other planets in our Solar System. Like the Earth, it has had a varied geological and climatological history[1]. Most of the planetary processes familiar to us here on Earth have apparently operated also on Mars, although under very different conditions, and perhaps at different scales and rates. Of particular importance is that Mars is the only planet in our Solar System, other than Earth, where liquid water has had a significant role in the evolution of the surface[2]. This fact, together with indications that Mars' climate may have been more Earth-like in the past[3], has led to speculation that some form of indigenous life could have developed there[4], or that the planet may have been colonized successfully by terrestrial life as a result of interplanetary transfer of meteorites[5]. These possibilities have been further stimulated by the finding of enigmatic structures and mineralogical relations in martian meteorites, which have been interpreted as possibly of biological origin[6]. An additional stimulus to Mars exploration is that it will surely be the first planet outside the Earth–Moon system to be visited by humans.

Strategic issues

While the long-term prospects for Mars exploration may include manned missions, the present exploration strategy is robotic and largely science driven, although constrained, of course, by the practicalities of budgets, schedules and technical feasibility. Determination of many environmental factors relevant to human exploration are, however, encompassed in the science goals. In recent years the United States has adopted an exploration strategy informally referred to as faster, better and cheaper. It involves launching to Mars many small, relatively low-cost missions, with narrowly focused science objectives, rather than large, costly complex missions with comprehensive science goals. The intent has been to drive down costs and to distribute risk across several missions so that a single failure will not catastrophically disrupt the whole programme. The strategy was adopted by the US Mars Program after the loss of Mars Observer in 1993. Before this time, planetary missions had grown so costly and complex that only one mission could be launched each decade. In contrast, since adopting the faster-better-cheaper strategy, the United States has launched five missions to Mars alone. The strategy has, however, had only mixed success. Although Pathfinder and Mars Global Surveyor were enormously successful, two Mars spacecraft were lost at Mars in 1999, probably because costs were so reduced that unacceptably high risks were taken. Despite the two failures, multiple, small missions still form the basis of the US strategic plan for Mars, although, in light of the failures, more attention is being paid to containing risks.

The orbital motions of Earth and Mars cause opportunities to launch spacecraft to Mars to recur every 26 months. The United States plans to launch at least one, and sometimes two, spacecraft to the planet at every opportunity for at least the next decade. In addition, the European Space Agency plans a launch in 2003 and France and Italy are planning to launch vehicles to the planet later within the decade, as described below. Thus, the exploration of Mars is truly international. Strategic planning meetings have multinational representation, most payloads are international, and some missions may be dependent on another agency for some essential element, such as telecommunications. Information on the various national plans is exchanged through the International Mars Working Group with representation from 11 nations.

The three basic science elements of Mars exploration are searching for evidence for past or present life, elucidating the evolution of the solid planet, and determining the climate history. Although the search for life is a primary objective, it entails high risk in that there may never have been any biological activity on the planet. Thus, the prudent strategy is, while pursuing the search for life, to continue to address the more general objectives concerning the evolution of the planet and its atmosphere. Mars is a very diverse planet with an area roughly the same as the land area of the Earth. Expectations are that if life ever evolved on the planet, or if there is life there today, the evidence will be preserved only in rare locations where conditions for fossil preservation or for sustaining life are met. The search-for-life strategy is, therefore, to first map the planet globally from orbit in an attempt to better understand what is where and to search for locations where water, warmth and nutrients may have been available to support life[7]. The global data will also enable us to reconstruct the broad outlines of the geological and climate history. The next step is to make more detailed observations of targets of interest both from orbit and on the ground. Finally, armed with the global and local knowledge, sites will be picked for comprehensive *in situ* life-detection experiments and sample-return missions. Meanwhile, experiments addressing objectives less directly concerned with life detection, such as achieving a better understanding of the circulation of the atmosphere or the structure of the

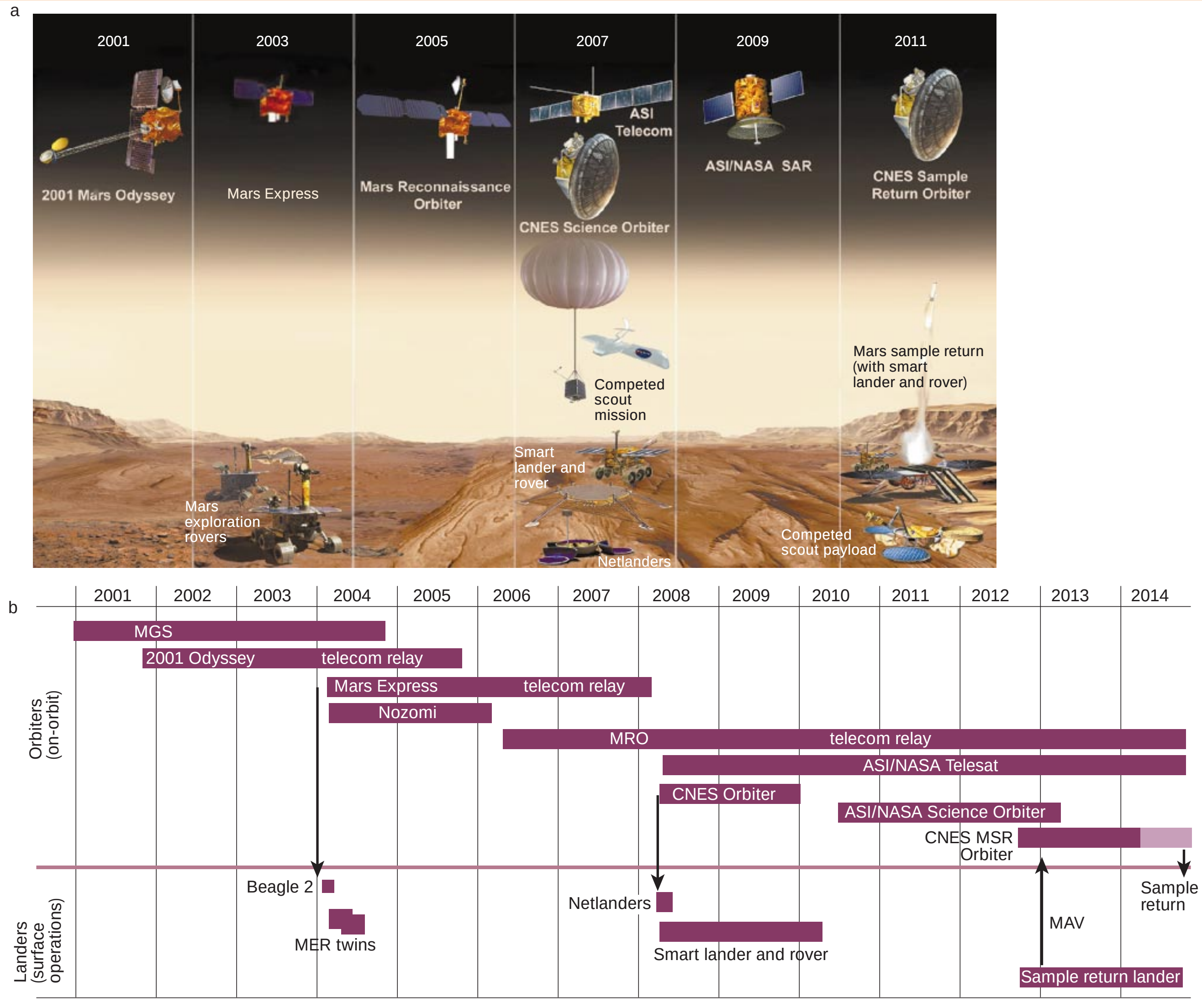

Figure 1 Envisaged mission sequence. **a**, Cartoon showing the different types of spacecraft to be launched to Mars in the next decade. The dates indicate the year the spacecraft is launched. **b**, The bars indicate the times that different spacecraft are expected to be operating at Mars (CNES and ASI are respectively the French and Italian space agencies).

interior, will be interleaved with the other missions. The strategy thus allows different high-priority investigations to be undertaken in parallel.

One of the main issues in the long-range strategic plan is when to return samples. Chemical and isotopic measurements can typically be done in terrestrial laboratories with precisions and sensitivities that are orders of magnitude better than are possible *in situ*. Other techniques, such as precise age determination and detection of microfossils, are so complicated and require such intricate sample preparation as to be impractical on a distant planet in the foreseeable future. Moreover, it is impossible to know a priori what are the most critical measurements to make *in situ*, and how best to make them. In contrast, having samples here on Earth allows the full analytical capability of the science community to be applied to them. The measurement strategy can shift in response to previous analytical results, and new techniques can be developed, as suggested by the samples themselves. Many researchers believe that the crucial questions of the age of surface materials, the nature of changes in climate, and whether life ever arose on the planet will not be answered definitively until we have here on Earth a well documented set of samples that are representative of the planet's variety. But sample return is expensive and technically challenging. Several new capabilities must be developed, such as autonomous launch from the martian surface and rendezvous in Mars orbit. The costs of developing these capabilities must be spread over several years. Moreover, it is argued that our knowledge of Mars is currently insufficient to know where to go to collect the samples that are most likely to resolve the question of whether there has ever been life on the planet. Preservation of fossils or evidence of biological activity requires special conditions; if there is life today, it is likely to be found only in very local niches. Because we are likely to get samples from only a few places, it is argued, we should be choose them particularly carefully. As a result of these technological and scientific challenges, a sample-return mission is unlikely to be launched before 2010, despite its importance.

Another argument raised against an early sample return is that if life exists on Mars today it could present a hazard to terrestrial life on Earth[8]. Almost everyone who has examined this problem has concluded that the chances that returned samples present a hazard is extremely small. After all, numerous martian meteorites fall on the Earth every year. Nevertheless, we cannot prove that the probability that the samples are harmful is zero. Accordingly, any sample returned to Earth must either be sterilized or returned in such a manner that the risk of inadvertent release is extremely low. Sterilization undermines the rationale for the samples, as in the process the materials of most interest are likely to be altered or destroyed. Thus, the focus on sample-return studies has been on designing systems to return samples to Earth in sealed containers that would be opened only in stringently controlled laboratory conditions[9]. Because of such issues of back contamination, some biologists have argued that, rather than returning samples, we should concentrate on developing sophisticated life-detection techniques that could be used at Mars, thereby by-passing the contentious problems of containment and hazard assessment.

The next decade

The next decade will be an active one for Mars exploration. As indicated above, missions will be sent to Mars at every 26-month opportunity, and on most opportunities there will be multiple launches. Figure 1 shows the currently envisaged mission sequence. The missions up to the 2005 launch opportunity are being implemented and, barring unforeseen circumstances, will be launched as indicated. Missions beyond 2005 are less certain. One consideration in the US strategy that was revised after the failures in 1999 was to have, where possible, orbiter missions succeed each other every four years, and likewise with lander missions. This was to enable lessons learned from one mission to be incorporated into a similar mission downstream. Thus, orbiter missions are to be launched by the United States in 2001, 2005 and 2009, whereas lander missions are to be launched in 2003, 2007 and 2011. The early non-US missions, having been started before the revised strategy, are interleaved with the alternating orbiter and lander missions.

Mars Global Surveyor was injected into Mars orbit in September 1997, and has been returning data ever since. It has imaged a few per cent of the surface at resolutions of 1.5–8 m pixel^{-1} (ref. 10), determined elevations of the whole planet at a spatial resolution of a few hundred metres and a vertical resolution of better than 1 m (ref. 11), and obtained thermal infrared spectra of the entire surface with a spatial resolution of 3 km (ref. 12). It has also determined the gravity field to degree and order of roughly 100 (ref. 13) and discovered large crustal magnetic anomalies which indicate that early Mars once had a strong magnetic field[14]. The spacecraft is currently making detailed observations of potential landing sites for subsequent missions, and in particular the 2003 rovers. It also now seems likely that Mars Global Surveyor will survive long enough to act as a data relay for other missions.

The next Mars mission is Mars Odyssey (2001), which will be placed in Mars orbit in October 2001. It carries three experiments. A gamma ray spectrometer will map the elemental composition of the surface globally at a spatial resolution of 250–300 km. A thermal emission imaging system will acquire infrared spectral images with a spatial resolution of 100 m of locations on the surface of special interest. This experiment is of particular interest for choosing landing sites for future missions as it may locate chemical anomalies such as might be caused by hydrothermal activity. The third experiment, MARIE (for Mars Radiation Environment Experiment), is intended to characterize the galactic cosmic radiation environment around Mars, in anticipation of engineering design choices that must be made for future human missions to the planet. Odyssey is also designed to act as a relay for the rovers to be launched in 2003.

Several missions will be launched to Mars in 2003. The United States will launch two Mars Exploration Rovers. These will soft land on the surface in air bags like Mars Pathfinder did in 1997, but unlike Pathfinder, the rovers will be independent of the landing system and be free to move away from the landing point. The landers are expected to survive on the surface for at least 90 days, during which they will perform a variety of measurements on the local rocks and soils. The process of choosing and characterizing the landing sites is well underway. Candidates include the floor of the canyons, floors of large craters thought to have formerly contained lakes, the edge of the ancient heavily cratered highlands, and a region where Mars Global Surveyor detected coarse-grained haematite (an iron mineral believed to have been precipitated from water) at the surface. Also in 2003, the European Space Agency is scheduled to launch an orbiter called Mars Express. This will carry a German high-resolution camera capable of mapping much of the planet in stereo and colour. It will also carry a French near-infrared spectrometer for determining surface mineralogy. In addition, a joint Italian/US radar surface sounder will attempt to detect liquid water down to depths of ~5 km below the surface. Other experiments will make measurements on the upper atmosphere and characterize the interaction between the planet and the solar wind. These plasma experiments will complement those of the Japanese spacecraft Nozomi, which will be in orbit around Mars at the same time. Mars Express will also deploy to the surface a small UK-built lander, called Beagle 2. It has a camera and a variety of detectors to measure the composition of the surface and atmosphere. Thus, 2004 will be a banner year for Mars exploration, with three landers on the surface and at least two and possibly four spacecraft in orbit, as the Odyssey and Mars Global Surveyor spacecraft could both survive that long and act as relay links.

In 2005, the US plans to launch a Mars Reconnaissance Orbiter. The payload for the orbiter has yet to be chosen, but it will probably include an atmospheric sounder designed to acquire multiple vertical profiles over one martian year, in order to characterize the atmosphere's circulation. Other likely instruments are a camera with resolution of tens of centimetres, and a visible-to-near-infrared spectrometer, both intended for use in identifying and characterizing future landing sites. There is also likely to be a radar sounder to detect subsurface water, but with a greater sensitivity and spatial resolution than that to be flown on Mars Express.

Beyond 2005, plans are much less certain. Likely possibilities include a 2007 launch of a French experiment to place four netlanders on the martian surface. Their main purpose will be to establish a seismic network to determine the internal structure of the planet, but they will also have imaging and geochemical sensors. At the same time, the United States plans to send additional rovers to the surface, to do longer-range exploration than those sent previously and to test some of the technologies needed for sample return. The United States will also request proposals from the science community for a small mission, termed a Scout, that could fill gaps left in the main programme. A joint US/Italian telecommunications satellite to support the various vehicles on the surface is also a possibility. What happens after 2007 will depend on budgets, on technological developments and also on what has been discovered about Mars in the intervening years. As indicated above, sample return is a high priority. By 2007 we should have acquired most of the orbital observations needed to select potentially fruitful landing sites, and have made enough measurements on the surface to provide the ground data required to interpret with confidence the orbiter remote-sensing data. We will also have considerable experience landing and operating vehicles on the surface. Thus, if we continue to maintain the 4-year spacing between landed missions, a 2011 launch of a sample-return mission is a possibility.

Beyond the next decade

What we do in the second decade of the millennium will depend on what we discover during the next few years, what funds are available, and whether we are any closer to committing to the exploration of the planet with people. Perhaps the most important factor governing what follows will be whether life is unambiguously detected either in martian meteorites, returned samples or by *in situ* experiments. Should life be detected, then the focus of subsequent exploration would surely be on characterizing that life and determining how and when it evolved. But the chance that life will be unambiguously detected is low. And whether or not it is detected, the desire for samples will remain high. We will want to acquire samples of different-aged igneous rocks, hydrothermal deposits, evaporites, lake beds, ancient channel sediments, deposits downstream of recently formed gullies, and so forth. The samples will be needed to further the search for life and to acquire more definitive information on the timing and nature of geological and climatological events. Long-lived rovers that can travel hundreds of kilometres with sophisticated geochemical and life-detection payloads will no doubt be advocated in order to sample a wide variety of geological units and possible biological environments. Such missions could be coupled with a capability for returning samples so that we can obtain a suite of samples representative of the planet's variety. Suggestions have also been advanced to drill into the surface to reach depths where liquid water might be stable today, and where life might still survive, as it does deep within the Columbia River basalts in eastern Washington[15]. Drill cores from the polar layered terrains would be of particular interest for unravelling the recent climate history. Other possibilities that have been suggested include low-flying balloons and aircraft to detect local subsurface water and thermal anomalies, and deploying global seismic and meteorological networks. Most of these suggestions do not readily fit within the faster-better-cheaper mould. But if we are to have a long-term exploration programme, we will need larger, more complicated missions than are currently being flown.

A major issue in the long-term plan is the role of human exploration. Opinions differ markedly on the role of humans. Some argue that humans should not set foot on the planet until it has been demonstrated that there is no life on Mars today. Humans would inevitably be accompanied by terrestrial microbial life that might compete with any indigenous life, thereby destroying or altering it. Humans could also return martian microbes to Earth, and so put some terrestrial life at risk. Others argue that such concerns are overstated, that the chances of there being life on Mars today is close to zero, and that even if there is life and it is brought back to Earth, it could not compete with our planet's terrestrial organisms, which occupy every conceivable niche. Another issue is what purpose it would serve to send people to Mars. The enormous cost of transporting people simply to perform science experiments and fieldwork hardly seems justifiable. For the cost of one manned mission, hundreds of robots could be deployed all over the planet to do fieldwork, collect samples and deploy instruments. Some advocates of manned missions assert that the rationale for human missions to Mars is really not practical but spiritual. The will to explore is deeply rooted in human nature. Exploration lifts us above the humdrum concerns of food and shelter and provides us with feelings of awe, wonderment and pride. If people are ultimately to go to Mars, it may well be such considerations that drive us there. But human exploration is a long way off. Meanwhile, there is an entire planet to explore and possibly an entirely new biology to discover. □

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