ExoMars

Searching for Life on the Red Planet

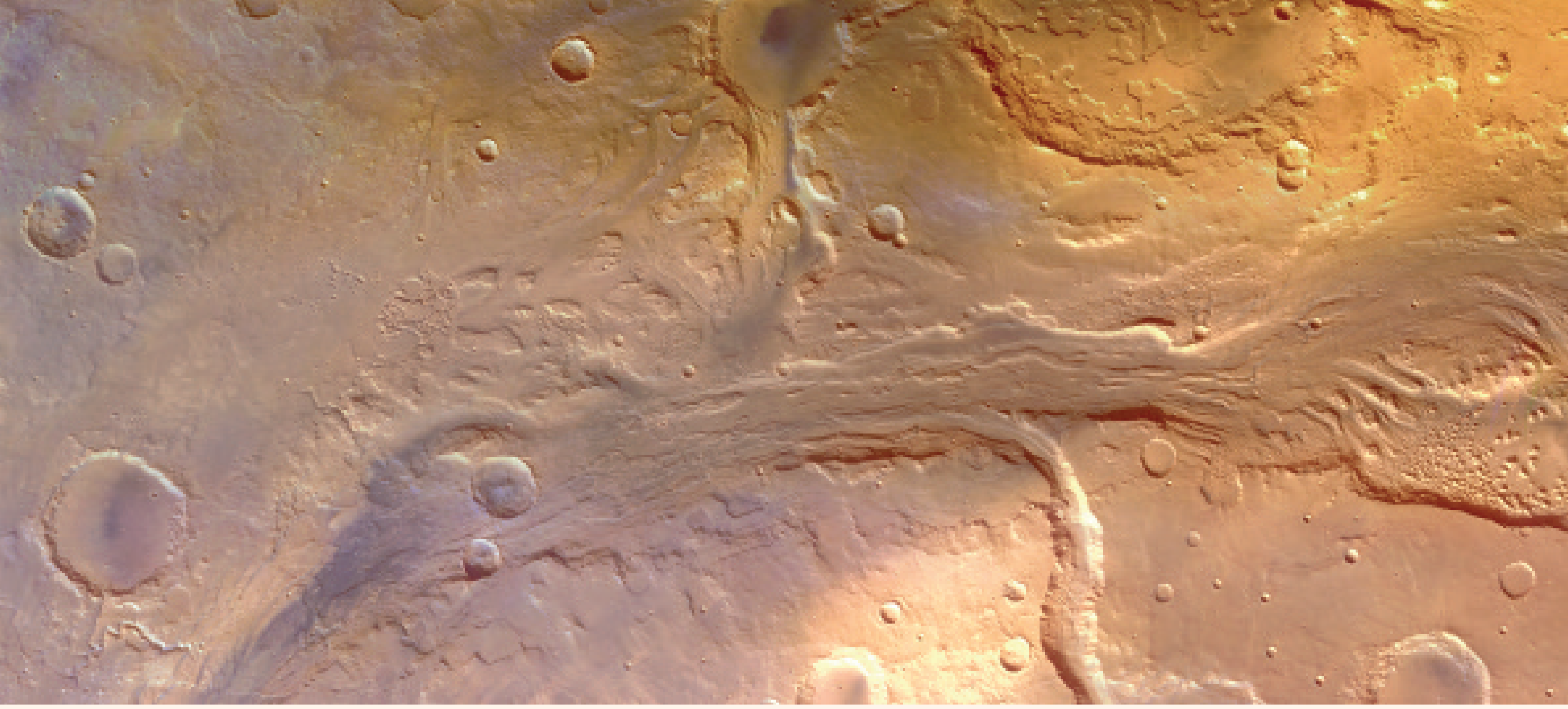
Jorge Vago, Bruno Gardini, Gerhard Kminek, Pietro Baglioni, Giacinto Gianfiglio, Andrea Santovincenzo, Silvia Bayón & Michel van Winnendael
Directorate for Human Spaceflight, Microgravity and Exploration Programmes, ESTEC, Noordwijk, The Netherlands

Establishing whether life ever existed on Mars, or is still active today, is an outstanding question of our time. It is also a prerequisite to prepare for future human exploration. To address this important objective, ESA plans to launch the ExoMars mission in 2011. ExoMars will also develop and demonstrate key technologies needed to extend Europe's capabilities for planetary exploration.

Mission Objectives

ExoMars will deploy two science elements on the Martian surface: a rover and a small, fixed package. The Rover will search for signs of past and present life on Mars, and characterise the water and geochemical environment with depth by collecting and analysing subsurface samples. The fixed package, the Geophysics/Environment Package (GEP), will measure planetary geophysics parameters important for understanding Mars's evolution and habitability, identify possible surface hazards to future human missions, and study the environment.

The Rover will carry a comprehensive suite of instruments dedicated to exobiology and geology: the Pasteur payload. It will travel several kilometres searching for traces of life, collecting and analysing samples from inside surface rocks and by drilling down to 2 m. The very powerful combination of mobility and accessing locations where organic molecules may be well-preserved is unique to this mission.



ExoMars will also pursue important technology objectives aimed at extending Europe's capabilities in planetary exploration. It will demonstrate the descent and landing of a large payload on Mars; the navigation and operation of a mobile scientific platform; a novel drill to obtain subsurface samples; and meet challenging planetary protection and cleanliness levels necessary to achieve the mission's ambitious scientific goals.

The Search for Life

Exobiology, in its broadest terms, denotes the study of the origin, evolution and distribution of life in the Universe. It is well established that life arose very early on the young Earth. Fossil records show that life had already attained a large degree of biological sophistication 3500 million years ago. Since then, it has proved extremely adaptable, colonising even the most disparate ecological habitats, from the very cold to the very hot, and spanning a wide range of pressure and chemical conditions. For organisms to have emerged and evolved, water must have been readily available on our planet. Life as we know it relies, above all else, upon liquid water. Without it, the metabolic activities of living cells are not possible. In the absence of water, life either ceases or slips into quiescence.

Mars today is cold, desolate and dry. Its surface is highly oxidised and exposed to sterilising and degrading ultraviolet (UV) radiation. Low temperature and pressure preclude the existence of liquid water; except, perhaps, in localised environments, and then only episodically. Nevertheless, numerous features such as large channels, dendritic valley networks, gullies and sedimentary rock formations suggest the past action of surface liquid water on Mars – and lots of it. In fact, the sizes of outflow channels imply immense discharges, exceeding any floods known on Earth.

Mars's observable geological record spans some 4500 million years. From the number of superposed craters, the oldest terrain is believed to be about 4000 million years old, and the youngest possibly less than 100 million years. Most valley networks are ancient (3500–4000 million years), but as many as 25–35% may be more recent. Today, water on Mars is only stable as ice at the poles, as permafrost in widespread underground deposits, and in trace amounts in the atmosphere. From a biological perspective, past liquid water itself motivates the question of life on Mars. If Mars' surface was warmer and wetter for the first 500 million years of its history, perhaps life arose independently there at more or less the same time as it did on Earth.

An alternative pathway may have been the transport of terrestrial organisms embedded in meteoroids, delivered from Earth. Yet another hypothesis is that life may have developed within a warm, wet subterranean environment. In fact, given the discovery of a flourishing biosphere a kilometre below Earth's surface, a similar vast microbial community may be active on Mars, forced into that ecological niche by the disappearance of a more benign surface environment. The possibility that life may have evolved on Mars during an earlier period surface water, and that organisms may still exist underground, marks the planet as a prime candidate in the search for life beyond Earth.

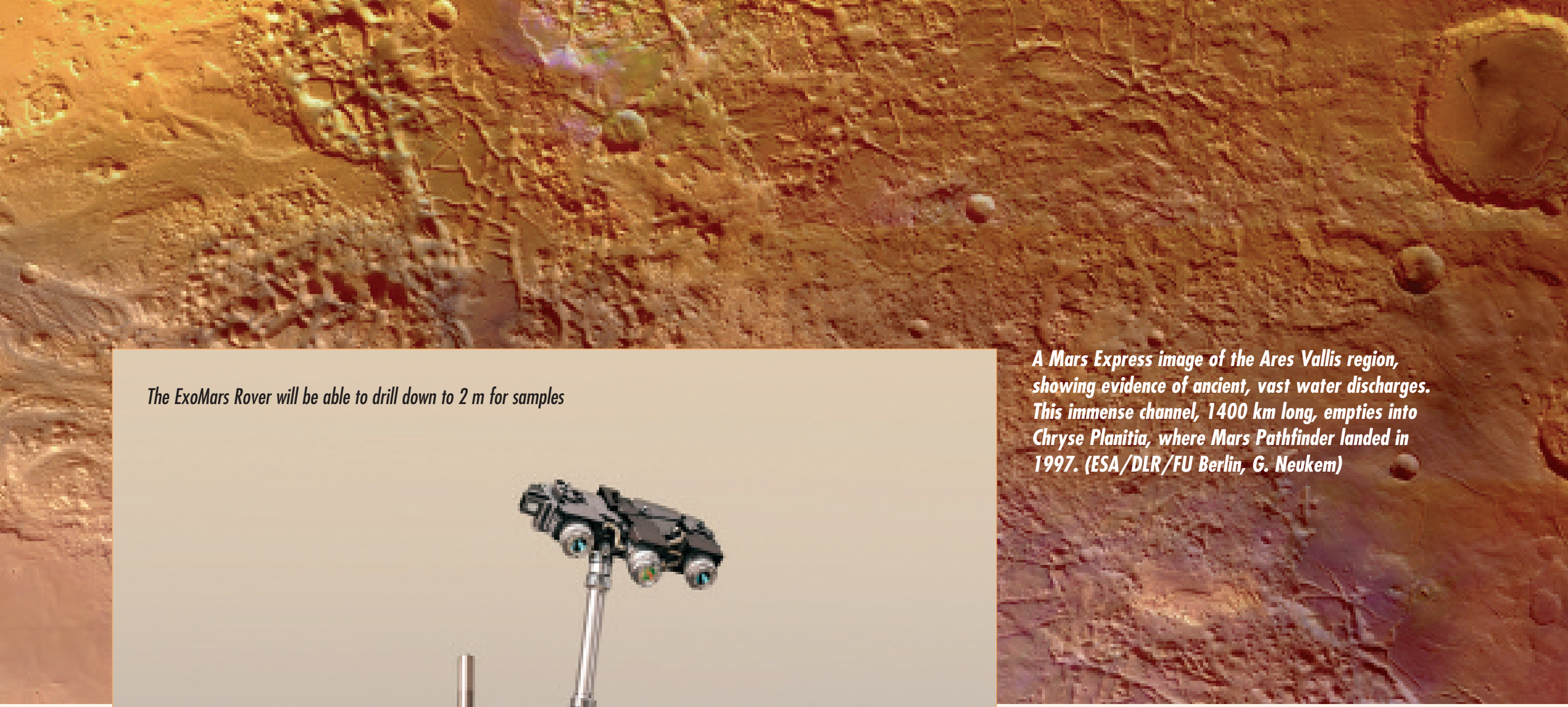
Hazards for Manned Operations on Mars

Before we can contemplate sending astronauts to Mars, we must understand and control any risks that may pose a threat to a mission's success. We can begin to assess some of these risks with ExoMars.

Ionising radiation is probably the single most important limiting factor for human interplanetary flight. To evaluate its danger and to define efficient mitigation strategies, it is desirable to incorporate radiation-monitoring capabilities during cruise, orbit and surface operations on precursor robotic missions to Mars.

Another physical hazard may result from the basic mechanical properties of the Martian soil. Dust particles will invade the interior of a spacecraft during surface operations, as shown during Apollo's operations on the Moon. Dust inhalation can pose a threat to astronauts on Mars, and even more so under microgravity during the return flight to Earth. Characteristics of the soil, including the sizes, shapes and compositions of individual particles, can be studied with dedicated *in situ* instrumentation. However, a more in-depth assessment, including a toxicity analysis, requires the return of a suitable Martian sample.

Reactive inorganic substances could present chemical hazards on the surface. Free radicals, salts and oxidants are very aggressive in humid conditions such as the lungs and eyes. Toxic metals, organics and pathogens are also potential hazards. As with dust, chemical hazards in the soil will contaminate the interior of a spacecraft during surface operations. They could damage the health of astronauts and the



A Mars Express image of the Ares Vallis region, showing evidence of ancient, vast water discharges. This immense channel, 1400 km long, empties into Chryse Planitia, where Mars Pathfinder landed in 1997. (ESA/DLR/FU Berlin, G. Neukem)

The ExoMars Rover will be able to drill down to 2 m for samples

operation of equipment. Many potential inorganic and organic chemical hazards may be identified with the ExoMars search-for-life instruments.

Geophysics Measurements

The processes that have determined the long-term 'habitability' of Mars depend on the geodynamics of the planet, and on its geological evolution and activity. Important issues still need to be resolved. What is Mars' internal structure? Is there any volcanic activity on Mars? The answers may allow us to extrapolate into the past, to estimate when and how Mars lost its magnetic field, and the importance of volcanic outgassing for the early atmosphere.

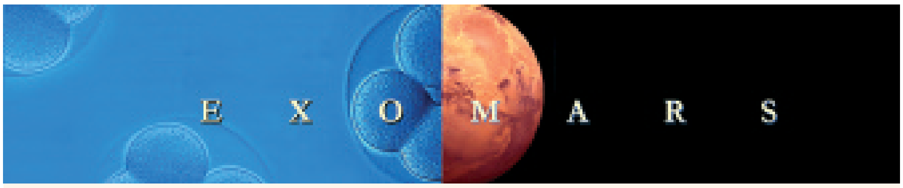
ExoMars will also carry the Geophysics/Environment Package, accommodated on the Descent Module and powered by a small radioisotope thermal generator.

Searching for Signs of Life

If life ever arose on the Red Planet, it probably did so when Mars was warmer and wetter, during its initial 500–1000 million years. Conditions then were similar to those on early Earth: active volcanism and outgassing, meteoritic impacts, large bodies of liquid water, and a mildly reducing atmosphere. We may reasonably expect that microbes quickly became global. Nevertheless, there is inevitably a large measure of chance involved in finding convincing evidence of ancient, microscopic life forms.

On Earth's surface, the permanent presence of running water, solar-UV radiation, atmospheric oxygen and life itself quickly erases all traces of any exposed, dead organisms. The only opportunity to detect them is to find their biosignatures encased in a protective environment, as in suitable rocks. However, since high-temperature metamorphic processes and plate tectonics have reformed most ancient terrains, it is very difficult to find rocks on Earth older than 3000 million years in good condition. Mars, on the other hand, has not suffered such widespread tectonic activity. This means there may be rock formations from the earliest period of Martian history that have not been exposed to high-temperature recycling. Consequently, well-preserved ancient biomarkers may still be accessible for analysis.

Even on Earth, a major difficulty in searching for primitive life is that, in essence, we are looking for the remnants of minuscule beings whose fossilised forms can be simple enough to be confused with tiny mineral precipitates. This issue lies at the heart of a heated debate among



Mission strategy to achieve ExoMars's scientific objectives:

1 To land on, or be able to reach, a location with high exobiology interest for past and/or present life signatures, i.e. access to the appropriate geological environment.

2 To collect scientific samples from different sites, using a Rover carrying a drill capable of reaching well into the soil and surface rocks. This requires mobility and access to the subsurface.

3 At each site, to conduct an integral set of measurements at multiple scales: beginning with a panoramic assessment of the geological environment, progressing to smaller-scale investigations on interesting surface rocks using a suite of contact instruments, and culminating with the collection of well-selected samples to be studied by the Rover's analytical laboratory.

4 To characterise geophysics and environment parameters relevant to planetary evolution, life and hazards to humans.

To arrive at a clear and unambiguous conclusion on the existence of past or present life at the Rover sites, it is essential that the instrumentation can provide mutually reinforcing lines of evidence, while minimising the opportunities for alternative interpretations.

It is also imperative that all instruments be carefully designed so that none is a weak link in the chain of observations; performance limitations in an instrument intended to confirm the results obtained by another should not generate confusion and discredit the whole measurement.

The science strategy for the Pasteur payload is therefore to provide a self-consistent set of instruments to obtain reliable evidence, for or against, the existence of a range of biosignatures at each search location.

Spacecraft:	Carrier plus Descent Module (including Rover and GEP) Data-relay provided by NASA
Launch:	May–June 2011, from Kourou on Soyuz-2b (backup 2013)
Arrival:	June 2013 (backup 2015)
Landing:	Direct entry, from hyperbolic trajectory, after the dust storm season. Latitudes 15°S–45°N, all longitudes, altitude: <0 m, relative to the MGS/MOLA* zero level
Science:	Rover with Pasteur payload: mass 120–180 kg, includes: Drill System/SPDS and instruments (8 kg); lifetime 180 sols Geophysics Environment Package (GEP): mass <20 kg; includes: instruments (~4 kg); lifetime 6 years
Ground Segment:	Mission control and mission operations: ESOC Rover operation on Mars surface: Rover Operations Centre GEP operations: to be decided

**MGS/MOLA: Mars Global Surveyor/Mars Orbiter Laser Altimeter*

palaeobiologists. It is therefore doubtful that any one signature suggestive of life – whether it is an image implying a biostructure, an interesting organic compound or a fractionated isotopic ratio – may reliably demonstrate a biogenic origin. Several independent lines of evidence are required to construct a compelling case. ExoMars must therefore pursue a holistic search strategy, attacking the problem from multiple angles, including geological and environmental investigations (to characterise potential habitats), visible examination of samples (morphology) and spectrochemical composition analyses.

In 1976, the twin Viking landers conducted the first *in situ* measurements focusing on the detection of organic compounds and life on Mars. Their biology package contained three experiments, all looking for signs of metabolism in soil samples. One, the labelled-release experiment, produced provocative results. If other information had not been also available, these data could have been interpreted as proof of biological activity. However, theoretical modelling of the atmosphere and regolith chemistry hinted at powerful oxidants that could more-or-less account for the results of the three experiments. The biggest blow was the failure of the Viking gas chromatograph mass spectrometer (GCMS) to find evidence of organic molecules at the parts-per-billion level.

With few exceptions, the majority of the scientific community has concluded that the Viking results do not demonstrate the presence of life. Numerous attempts have been made in the laboratory to simulate the Viking reactions. While some have reproduced certain aspects, none has succeeded entirely. Incredibly, 30 years after Viking, the crucial chemical oxidant hypothesis remains untested. ExoMars will include a powerful instrument to study oxidants and their relation to organics distribution on Mars.

Undoubtedly, the present environment on Mars is exceedingly harsh for the widespread proliferation of surface life: it is simply too cold and dry, not to mention the large doses of UV. Notwithstanding

Recommended Pasteur Exobiology Instruments[1]

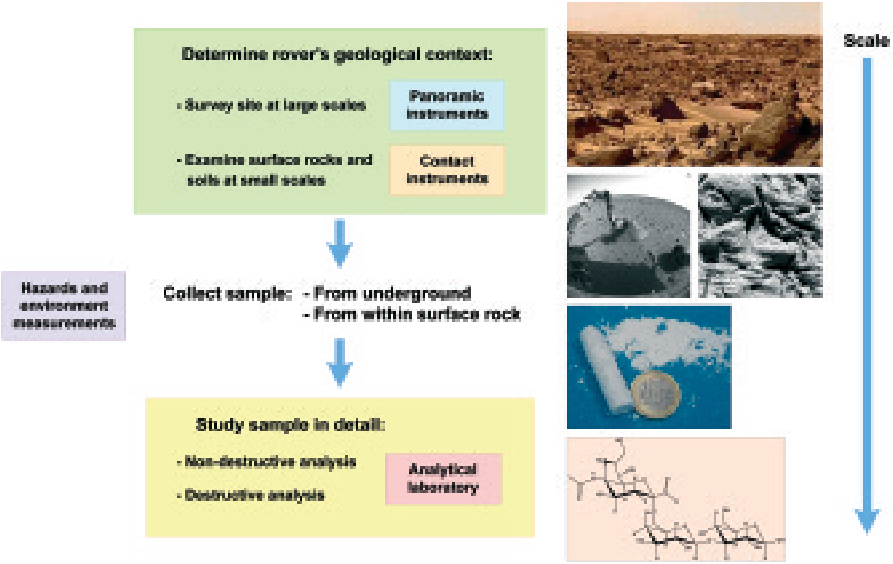
Panoramic Instruments	To characterise the Rover's geological context (surface and subsurface). Typical scales span from panoramic to 10 m, with a resolution of the order of 1 cm for close targets.
Panoramic Camera System	2 wide-angle stereo cameras and 1 high-resolution camera; to characterise the Rover's environment and its geology. Also very important for target selection.
Infrared (IR) Spectrometer	For the remote identification of water-related minerals, and for target selection.
Ground Penetrating) Radar (GPR)	To establish the subsurface soil stratigraphy down to 3 m depth, and to help plan the drilling strategy.
Contact Instruments	To investigate exposed bedrock, surface rocks and soils. Among the scientific interests at this scale are: macroscopic textures, structures and layering; and bulk mineralogical and elemental characterisation. This information will be fundamental to collect samples for more detailed analysis. The preferred solution is to deploy the contact instruments using an arm-and-paw arrangement, as in Beagle-2. Alternatively, in case of mass limitations, they could be accommodated at the base of the subsurface drill.
Close-Up Imager	To study rock targets visually at close range (cm) with sub-mm resolution.
Mössbauer Spectrometer	To study the mineralogy of Fe-bearing rocks and soils.
Raman-LIBS[2] external heads	To determine the geochemistry/organic content and atomic composition of observed minerals. These optical are external heads connected to the instruments inside the analytical laboratory.
Support Instruments	These instruments are devoted to the acquisition and preparation of samples for detailed investigations in the analytical laboratory. They must follow specific acquisition and preparation protocols to guarantee the optimal survival of any organic molecules in the samples. The mission's ability to break new scientific ground, particularly for signs-of-life investigations, depends on these two instruments.
Subsurface Drill	Capable of obtaining samples from 0 m to 2 m depths, where organic molecules might be well-preserved. It also integrates temperature sensors and an IR spectrometer for borehole mineralogy studies.
Sample Preparation and Distribution System (SPDS)	Receives a sample from the drill system, prepares it for scientific analysis, and presents it to all analytical laboratory instruments. A very important function is to produce particulate material while preserving the organic and water content.
Analytical Laboratory	To conduct a detailed analysis of each sample. The first step is a visual and spectroscopic inspection. If the sample is deemed interesting, it is ground up and the resulting particulate material is used to search for organic molecules and to perform more accurate mineralogical investigations.
Microscope IR	To examine the collected samples to characterise their structure and composition at grain-size level. These measurements will also be used to select sample locations for further detailed analyses by the Raman-LIBS spectrometers.
Raman-LIBS	To determine the geochemistry/organic content and elemental composition of minerals in the collected samples.
X-ray Diffractometer (XRD)	To determine the true mineralogical composition of a sample's crystalline phases.
Urey (Mars Organics and Oxidants Detector)	Mars Organics Detector (MOD): extremely high-sensitivity detector (ppt) to search for amino acids, nucleotide bases and PAHs in the collected samples. Can also function as front-end to the GCMS. Mars Oxidants Instrument (MOI): determines the chemical reactivity of oxidants and free radicals in the soil and atmosphere.
GCMS	Gas chromatograph mass spectrometer to conduct a broad-range, very-high sensitivity search for organic molecules in the collected samples; also for atmospheric analyses.
Life-Marker Chip	Antibody-based instrument with very high specificity to detect present life reliably.

[1]Mass (without drill and SPDS): 12.5 kg. [2]LIBS: Laser-Induced Breakdown Spectroscopy.

Recommended Pasteur Environment Instruments[3]

Environment Instruments	To characterise possible hazards to future human missions and to increase our knowledge of the Martian environment.
Dust Suite	Determines the dust grain size distribution and deposition rate. It also measures water vapour with high precision.
UV Spectrometer	Measures the UV radiation spectrum.
Ionising Radiation	Measures the ionising radiation dose reaching the surface from cosmic rays and solar particle events.
Meteorological Package	Measures pressure, temperature, wind speed and direction, and sound.

[3]Mass: 1.9 kg. The Pasteur environment instruments are presently planned to be accommodated in the GEP.



The ExoMars surface science exploration scenario. The Rover will conduct measurements of multiple scales, starting with a panoramic assessment of the geological environment, progressing to more detailed investigations on surface rocks using a suite of contact instruments, and culminating with the collection of well-selected samples to be analysed in its laboratory

these hazards, basic organisms could still flourish in protected places: deep underground, at shallow depths in especially benign environments, or within rock cracks and inclusions.

The strategy to find traces of past biological activity rests on the assumption that any surviving signatures of interest will be preserved in the geological record, in the form of buried/encased remains, organic material and microfossils. Similarly, because current surface conditions are hostile to most known organisms, as when looking for signs of extant life, the search methodology should focus on investigations in protected niches: underground, in permafrost or within surface rocks. This means that there is a good possibility that the same sampling device and instrumentation may adequately serve both types of studies. The biggest difference is due to location requirements. In one case, the interest lies in areas occupied by ancient bodies of water over many thousands of years. In the other, the emphasis is on water-rich environments close to the surface and accessible to our sensors today. For the latter, the presence of permafrost alone may not be enough. Permafrost in combination with a sustained heat source, probably of volcanic or hydrothermal origin, may be necessary. Such warm oases can only be identified by an orbital survey of the planet. In the next few years, a number of remote-sensing satellites, like ESA's Mars Express and NASA's Mars Reconnaissance Orbiter (MRO), will determine the water/ice boundary across Mars and may help to discover such warm spots. If they do exist, they would be prime targets for missions like ExoMars.

On Earth, microbial life quickly became a global phenomenon. If the same explosive process occurred on the young Mars, the chances of finding evidence of it are good. Even more interesting would be the discovery and study of life forms that have successfully adapted to the modern Mars. However, this presupposes the prior identification of geologically suitable, life-friendly locations where it can be demonstrated that liquid water still exists, at least episodically throughout the year. For these reasons, the 'Red Book' science team advised ESA to focus on the detection of extinct life, but to build enough flexibility into the mission to be able to target sites with the potential for present life.

Mission Description

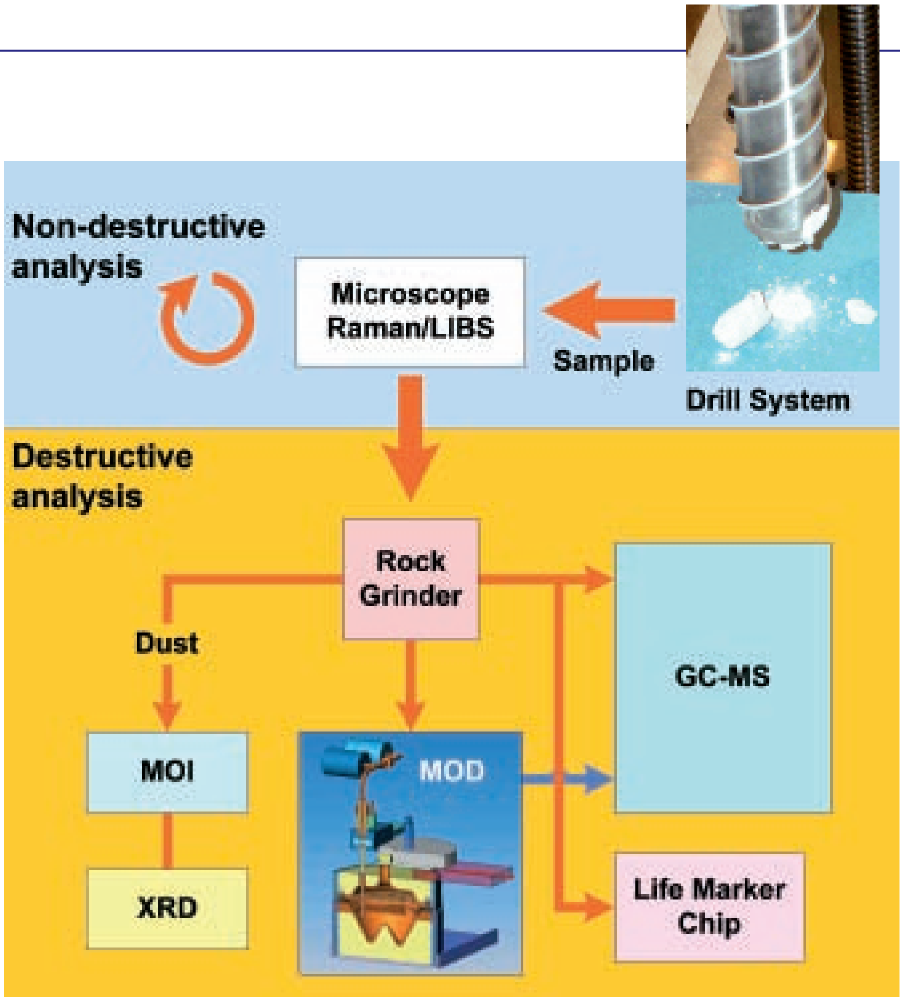
The baseline mission scenario consists of a spacecraft composite with a Carrier and a Descent Module, launched by a Soyuz-2b from Kourou. It will follow a 2-year 'delayed trajectory' in order to reach Mars after the dust-storm season. The Descent Module will be released from the hyperbolic arrival path, and land using either bouncing (non-vented, as in NASA's rovers) or non-bouncing (vented) airbags, and deploy the Rover and GEP. In the baseline mission, data-relay for the Rover will be provided by a NASA orbiter.

An alternative configuration, based on an Ariane-5 ECA launcher, may be implemented depending on programme, technical and financial considerations. In this option, the Carrier is replaced with an Orbiter that provides end-to-end data relay for the surface elements. The Orbiter will also carry a science payload to complement the results from the Rover and GEP, and provide continuity to the great scientific discoveries flowing from Mars Express.

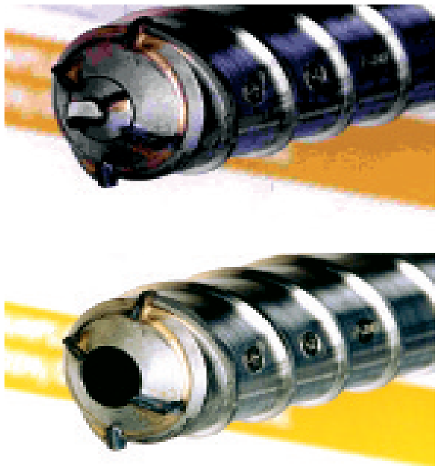
ExoMars is a search-for-life mission targeting regions with high life potential. It has therefore been classified as Planetary Protection category IVc. This, coupled with the mission's ambitious scientific goals, imposes challenging sterilisation and organic cleanliness requirements.

The ExoMars Rover

The Rover will have a nominal lifetime of 180 sols (about 6 months). This period provides a regional mobility of several kilometres, relying on solar array electrical power. The Pasteur model payload includes panoramic instruments (cameras, ground-penetrating radar and IR spectrometer; contact instruments for studying surface rocks (close-up imager and Mössbauer spectrometer), a subsurface drill to reach depths of 2 m and to collect specimens from exposed bedrock, a sample preparation and distribution unit, and the analytical laboratory. The latter includes a microscope, an oxidation sensor and a variety of



The analysis sequence within Pasteur's analytical laboratory



The Pasteur payload's drill-bit design concept. The drill's full 2 m extension is achieved by assembling four sections (one drill tool rod, with an internal shutter and sample-collection capability, plus three extension rods). The drill will also be equipped with an IR spectrometer for mineralogy studies inside the borehole. (Galileo Avionica)

instruments for characterising the organic substances and geochemistry in the collected samples.

A key element is the drill. The reason for the 2 m requirement is the need to obtain pristine sample material for analysis. Whereas the estimated extinction horizon for oxidants in the subsurface is several centimetres, damaging ionising radiation can penetrate to depths of around 1 m. Additionally, it is unlikely that loose dust may hold interesting biosignatures, because it has been moved around by wind and processed by UV radiation. In the end, organic substances may best be preserved within low-porosity material. Hence, the ExoMars drill must be able to penetrate and obtain samples from well-consolidated (hard) formations, such as sedimentary rocks and evaporitic deposits. Additionally, it must monitor and control torque, thrust, penetration depth and temperature at the drill bit. Grain-to-grain friction in a rotary drill can generate a heat wave in the sample, destroying the organic molecules that ExoMars seeks to detect. The drill must therefore have a variable cutting protocol, to dissipate heat in a science-safe manner. Finally, the drill's IR spectrometer will conduct mineralogy studies inside the borehole.

Conclusion

NASA's highly successful 2004 rovers were conceived as robotic geologists. They have demonstrated the past existence of long-lasting, wet environments on Mars. Their results have persuaded the scientific community that mobility is a must-have requirement for all future surface missions. Recent results from Mars Express have revealed multiple, ancient deposits containing clay minerals that form only in the presence of liquid water. This reinforces the hypothesis that ancient Mars may have been wetter, and possibly warmer, than it is today. NASA's 2009 Mars Science Laboratory will study surface geology and organics, with the goal of identifying habitable environments. ExoMars is the next logical step. It will have instruments to investigate whether life ever arose on the Red Planet. It will also be the first mission with the mobility to access locations where organic molecules may be well-preserved, thus allowing, for the first time, investigation of Mars' third dimension: depth. This alone is a guarantee that the mission will break new scientific ground. Finally, the many technologies developed for this project will allow ESA to prepare for international collaboration on future missions, such as Mars Sample Return.

Following the recent accomplishments of Huygens and Mars Express, ExoMars provides Europe with a new challenge, and a new opportunity to demonstrate its capacity to perform world-class planetary science.

ExoMars is now in Phase-B1 and is expected to begin Phase-B2 in mid-2007 and Phase-C/D in early 2008. esa