



CRITICAL ISSUES IN CONNECTION WITH HUMAN MISSIONS TO MARS: PROTECTION OF AND FROM THE MARTIAN ENVIRONMENT

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ABSTRACT

Human missions to Mars are planned to happen within this century. Activities associated therewith will interact with the environment of Mars in two reciprocal ways: (i) the mission needs to be protected from the natural environmental elements that can be harmful to human health, the equipment or to their operations; (ii) the specific natural environment of Mars should be protected so that it retains its value for scientific and other purposes. The following environmental elements need to be considered in order to protect humans and the equipment on the planetary surface: (i) cosmic ionizing radiation, (ii) solar particle events; (iii) solar ultraviolet radiation; (iv) reduced gravity; (v) thin atmosphere; (vi) extremes in temperatures and their fluctuations; and (vii) surface dust. In order to protect the planetary environment, the requirements for planetary protection as adopted by COSPAR for lander missions need to be revised in view of human presence on the planet. Landers carrying equipment for exobiological investigations require special consideration to reduce contamination by terrestrial microorganisms and organic matter to the greatest feasible extent. Records of human activities on the planet's surface should be maintained in sufficient detail that future scientific experimenters can determine whether environmental modifications have resulted from explorations. © 2002 COSPAR. Published by Elsevier Science Ltd. All rights reserved.

INTRODUCTION

Within the last years, the European Space Agency (ESA) has initiated several activities with regard to a potential European participation in human missions to Mars. These include the following actions:

- In 1998, ESA has set up an Interdirectorate Group de Réflexion to investigate the role Europe could play in an international cooperative initiative of a human mission to Mars and to develop a plan to enable European participation in an international Mars Human Exploration mission. Among other areas, radiation monitoring was considered as a key issue, which is already in the research plan for the ISS program, and which will provide basic information for the preparation of safe human missions to Mars.
- In 1999, ESA has launched a study on the search for life on Mars (Brack et al. 1999) that among others examined the ways in which a manned station on Mars might assist in further developing exobiology research on that planet and whether such a station would pose significant risks to the success of searching for life on Mars.
- In 2000, ESA has initiated the HUMEX study (Horneck et al. 2002) in order to critically assess the survivability and adaptation of humans to long-duration interplanetary and planetary environments.
- In 2001, ESA has started the Aurora Program with aims to set out a strategy for Europe's solar system exploration over the next 30 years - which among others also includes manned expeditions to Mars. To reach these goals, Europe will have to set up a realistic technological and scientific strategy which is based on the experience in Europe and determined by the requirements of such an international enterprise.

Activities associated with lander (robotic or human) missions to Mars will interact with the planetary environment in two reciprocal ways:

- (i) The mission needs to be protected from the natural environmental elements that can be harmful to human health, the equipment or to their operations. In addition, landers carrying equipment for exobiological investigations (e.g., search for signatures of extant or extinct life on Mars) require special consideration to reduce contamination by terrestrial microorganisms and organic matter to the greatest feasible extent in order to avoid false positive data.
- (ii) The specific natural environment of the planet should be protected so that it retains its value for scientific and other purposes as well as ethical issues. In this connection it might be necessary to record all human activities on the planet's surface in sufficient detail that future scientific experimenters can determine whether environmental modifications have resulted from these explorations.

THE ENVIRONMENT OF MARS AS RELEVANT TO HUMAN MISSIONS

Although the Martian climate has several similarities with that of the Earth, e.g., four seasons, length of days, the environment is dramatically different from that of the Earth (Table 1). The Martian seasons last about twice as long as those on Earth and they are more complex due to the high eccentricity of the Martian orbit. As a consequence, there exist large temperature asymmetries between the northern and the southern hemisphere. Martian gravity is about 3/8 that of the Earth and the atmospheric pressure is comparable to that on Earth at an altitude of more than 30 km. Compared to the surface conditions of the Earth, the surface radiation doses on Mars caused by cosmic rays are about 100 times higher. Below the surface, the Martian regolith provides some additional shielding, although the generation of secondary particles needs to be considered. So far, there are no radiation measurements conducted on the surface of Mars. Our knowledge about the radiation conditions on the surface of Mars and their biological effectiveness is based on a few radiation measurements outside the Earth orbit during the Apollo missions (Benton and Parnell, 1988; Bückner and Horneck, 1975), measurements in Earth orbit (Horneck, 1992; Reitz *et al.* 1998; Nicolet, 1989; Kiefer *et al.* 1996; Horneck *et al.* 1996) and model calculations (Kuhn and Artreya 1979; Wilson *et al.* 1993; Cockell, 2000).

Table 1. Martian Environmental Surface Elements as Relevant to Human Missions Compared to the Terrestrial Conditions (from Horneck *et al.* 2001)

Environmental element	Mars	Earth
Cosmic ionizing radiation	100-200 mSv/a	1-2 mSv/a
Solar particle events	up to ~ 100 mSv/h	not applicable
Solar irradiance	589 W/m ²	1368 W/m ²
Solar UV radiation spectrum	$\lambda \geq 200$ nm	$\lambda \geq 290$ nm
Length of day	24h37'22.7"	23h56'4.1"
Length of year	687 d	365 d
Gravity	$0.377 \times g$	$1 \times g$
Atmosphere	95.3 % CO ₂	78.1 % N ₂
	2.7 % N ₂	20.9 % O ₂
	1.6 % Ar	0.03 % CO ₂
	0.1 % O ₂	
Pressure	~ 600 Pa	10 ⁵ Pa
Atmospheric shielding	16 g/cm ²	1000 g/cm ²
Diurnal temperature range	-90°C to - 30 °C (Viking data)	10°C to 20°C (Standard atmosphere)
Others	Surface dust / dust storms	

Table 2. Annual Dose Equivalent at the Martian Surface (from Wilson et al. 1993)

Condition	Annual dose equivalent (mSv/a) at altitude of			
	0 km	4 km	8 km	12 km
Mass shielding (g/cm ²)	16	11	7	5
Galactic cosmic rays	113	134	158	186
Solar particle event	40-90	90-110	130-210	160-220

The lack of an effective magnetic field and the low atmospheric pressure of Mars allow a substantial portion of the radiation from space to reach the surface of Mars. At the reference level, i.e. at a pressure of 610 Pa (6.1 mbar), the mass shielding of the mainly CO₂ atmosphere amounts to 16 g/cm² (Wilson et al. 1993). Table 2 shows the annual dose equivalent rates in Sievert (Sv) calculated for several altitudes on Mars. They amount to 100 to 200 Sv/a, depending on altitude. The intensity of the cosmic radiation is also a function of the direction of the incident particles: with increasing zenith angle the amount of protection increases.

The sun itself is an additional source of particles impinging on Mars. In solar particle events (SPEs) accompanied with sudden brightness in the solar disk, charged particles, mainly protons, some helium and heavier ions, with energies up to several GeV are emitted. Their occurrence is linked to the solar cycle with a higher probability at the end of a solar maximum. Due to absorption by the atmosphere, only part of the particles of SPEs reaches the surface of Mars (Table 2). The total annual dose rate as the sum of the annual galactic cosmic ray dose rate and the dose contributed by one large SPE has been estimated to range up to 240 mSv/a (Wilson et al. 1993).

An additional minor radiation exposure comes from emissions from primordial radionuclides of Mars itself. The natural radioactivity of the known Martian meteorites collected on Earth reaches annual dose rates up to 0.8 mGy/a. It is assumed that the dose equivalent owing to emissions from natural radionuclides on Mars is less than 1 % of that resulting from cosmic rays.

The intensity of solar electromagnetic radiation decreases with the square of the distance from the sun. At the orbit of Mars which is 1.52 AU distant from the sun, the solar radiation energy amounts to 595 W/m², which is approximately 43 % of that for the Earth. As solar radiation traverses the atmosphere of Mars, parts of it are absorbed, scattered or reflected by the molecules and aerosols of the atmosphere. Using radiative transfer models (Kuhn and Artreya, 1979; Cockell, 2000) the UV-radiation climate at the surface of Mars and its seasonal and geographic variation has been calculated. Due to absorption by CO₂ which comprises 95 % of the atmosphere, virtually no radiation at wavelengths below 200 nm reaches the surface of Mars. There is practically no O₃ in the atmosphere or temporarily only minor amounts with maximum 2 % of the mean terrestrial O₃ column thickness. As a consequence, all wavelengths of the solar UV spectrum above 200 nm impinge on the surface of Mars and this fraction of UV radiation is very much greater than that reaching the surface of the Earth, despite of the lower solar constant for Mars. If weighted for its DNA damaging capacity, the biologically effective dose of the Martian UV radiation is about 3 orders of magnitude higher than that on Earth, i.e. nearly comparable to that on in free space (Horneck et al. 1996; Cockell and Horneck, 2001). This intense UV-radiation at the surface of Mars has been suggested to be responsible for the lack of organics within surface samples (Biemann et al. 1976) and the active chemistry observed in the life detection experiments (Klein, 1992) of the two Viking missions by inducing photochemical reactions with the soil minerals resulting in aggressive peroxides.

PROTECTION OF HUMANS, THE EQUIPMENT AND THE OPERATIONS FROM THE HARMFUL ENVIRONMENT OF MARS

For a safe mission to Mars there are several environmental elements that need to be considered either individually or in combination. As described above (Table 1), the most important elements are as follows:

- (i) cosmic ionizing radiation and secondaries produced by interaction of the cosmic primaries with atoms and molecules of the atmosphere or shielding material as well as the human body itself;
- (ii) solar particle events that occur sporadically and may last over several days, which cause temporally substantial increases in the radiation dose;
- (iii) solar UV radiation which reaches the surface of Mars nearly unfiltered, including the biologically highly effective UV-C radiation (200-280 nm) (Horneck et al. 1995);

- (iv) reduced gravity of $0.377 \times g$ which is experienced by the crew after a trip in microgravity for nearly one year and a heavy g -load up to $6 \times g$ during landing;
 - (v) a very thin atmosphere of about 600 Pa, depending on altitude, consisting to about 95 % of CO_2 with negligible amounts of O_2 ;
 - (vi) extremes in temperatures which at the surface of Mars range between -123°C and $+25^\circ\text{C}$ with wide diurnal and seasonal fluctuations up to 100°C (Schofield *et al.*, 1997); however, these high fluctuations between midday and midnight temperatures pertain only to the top several mm of the surface and rapidly converge to a diurnal mean value at depths of 15 to 20 cm below the surface (Carr, 1996);
 - (vii) surface dust which can reach high concentrations in the atmosphere during dust storms.
- Some of these critical items and suitable countermeasures will be discussed in the following.

Protection from Ionizing Radiation

The surface of Mars is exposed to a high influx of ionizing radiation of galactic and solar origin due to the present absence of a magnetic field and to a low atmospheric shielding of 16 g/cm^2 . In order to assess the impact of radiation on humans and equipment and to employ protection measures, the following activities have been identified within the HUMEX study as necessary to start well in advance of any human planetary mission:

- to characterize the radiation field on the surface of Mars and its temporal variation by measurements from orbiters and landers and by developing adequate radiation transfer models. The first step has been done with the radiation dosimeter "Mars Radiation Environment Experiment" (MARIE) installed on the 2001 Mars Odyssey missions, that was launched on 7 April 2001. Using a spectroradiometer, for the first time the energy and charge distribution as well as the dose rate of the cosmic radiation was measured in Mars orbit. In June 2002, a rather quiet time, the dose rate ranged between 0.20 and 0.24 mGy/d (NASA, 2002). In addition, ESA plans to install a device to measure the RADiation climate on Mars as relevant to EXobiology (RADEX) on a Martian lander. The data provided by these instruments will be required to assess the radiation hazards for humans or any other living being on Mars and to establish radiation protection guidelines.
- to study the modification of this radiation in tissue equivalent material as well as in potential shielding material, such as regolith or the habitat walls. In this connection, MATROSHKA will be built by ESA and DLR, which consists of a tissue equivalent human dummy to record depth dose distribution when accommodated on the Russian segment of the International Space Station (ISS) (Figure 1).

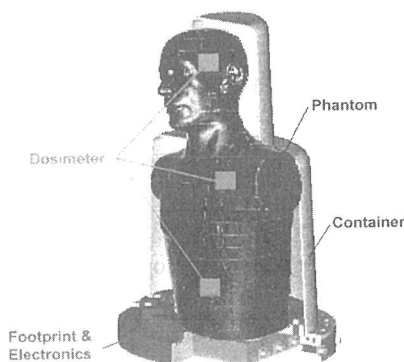


Fig 1. MATROSHKA, a tissue equivalent human dummy to record the depth dose distribution of radiation when accommodated outside of the Russian segment of the International Space Station.

- to establish a solar flare alert system, including an observation and warning station on Earth-orbiting satellites and on the surface itself (Smart and Shea, 2002).
- to study the biological effectiveness of single heavy ions of cosmic radiation in space (HZE particles) as well as at heavy ions accelerators on ground and to develop appropriate microdosimetry concepts. Because of the low flux of HZE particles (they contribute to approximately 1 % of the flux of particulate radiation in space), methods have been developed to localize precisely the trajectory of an HZE particle

relative to the biological object and to correlate the physical data of the particle relative to the observed biological effects along its path. In the Biostack method (Figure 2) visual track detectors are sandwiched between layers of biological objects in a resting state (Bücker and Horneck 1975). This method allows (i) to localize each HZE particle's trajectory in relation to the biological specimens; (ii) to investigate the responses of each biological individual hit separately, in regard to its radiation effects; (iii) to measure the impact parameter (i.e. the distance between the particle track and the sensitive target); (iv) to determine the physical parameters [charge (Z), energy (E) and linear energy transfer (LET)]; and finally (v) to correlate the biological effect with each HZE particle parameters. These studies provide important basic information in the attempts to assess the radiation risks for humans in space (Horneck, 1992).

- to study the biological effectiveness of the combined action of the different components of the radiation climate and potential interactions with other environmental factors, such as reduced gravity, and other physiological factors. Interactions of microgravity and radiation has been observed for embryogenesis in insects (Reitz et al. 1989), however repair of radiation-induced DNA damages was not disturbed by the microgravity environment in microorganisms and human fibroblasts in culture (Horneck et al. 1997, Horneck, 1999).

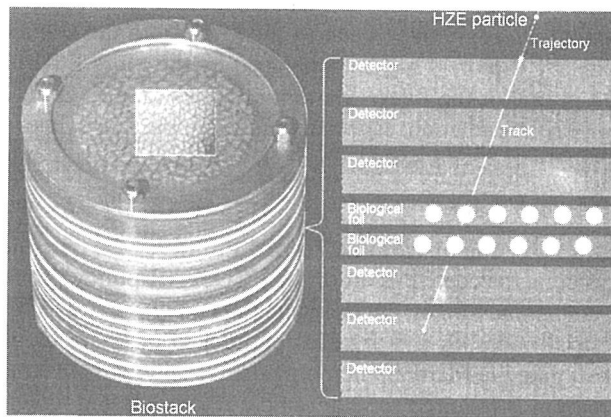


Fig. 2. Biostack experiments to study the biological effects of single particles of cosmic radiation.

- to establish radiation protection guidelines for human missions to Moon and Mars and to reach agreement between all nations involved. Above all, adequate shielding devices for habitats, working areas, rovers etc. are required and an on-line radiation monitoring system for personnel according to the radiation protection guidelines. The physical measurements should be complemented by biological dosimetry procedures, applying intrinsic biomarkers (e.g., chromosomal aberrations in lymphocytes) (Obe et al. 1999) as well as extrinsic biomarkers (e.g. biosensors for genotoxicity or cytotoxicity) (Ptitsyn et al. 1997; Horneck, 1998; Baumstark-Khan et al. 2001). The intrinsic biologically weighted responses to different radiation qualities - as provided by scoring chromosome aberrations - offers a so far unique possibility to monitor the exposure to the complex space radiation field in terms of a truly biologically weighted "equivalent" dose. This method also allows for detecting individual variations in radiation sensitivity among the crew members.

Protection from Solar UV Radiation

The surface of Mars is exposed to all photons of solar UV radiation of wavelengths above 200 nm. Especially the short-wavelength UV-C radiation (200 - 280 nm) is of high biological efficiency, because this wavelength range is effectively absorbed by the DNA resulting in mutations, cancer or cell killing (Horneck et al. 1995). Whereas humans can easily be protected against this harmful solar UV component, e.g., by the space suit or the walls and windows of the habitation module, the sensitivity of the external materials e.g., of the space suit and the habitation area, needs to be known. Using green houses for bioregenerative life support purposes requires also to select suitable windows with appropriate cutting off features: the plants might require a certain fraction of UV, especially in the UV-A and UV-B regime, whereas the short-wavelength part of UV-B and the UV-C radiation will certainly be harmful for their growth. In order to assess the impact from solar UV radiation on putative ecosystems

on Mars, it is recommended to study in simulation experiments and *in-situ* on board of the International Space Station the impact of the broad spectrum of extraterrestrial UV radiation on materials exposed to it, and the potential synergistic effects with other environmental parameters, such as vacuum and high temperature fluctuations. A first step will be done by the ROSE consortium to study the Responses of Organisms to Space Environment in the EXPOSE facility to be mounted on the external part of the International Space Station (Horneck *et al.* 1999). It is also necessary to establish guidelines for human exposure to the solar UV-spectrum. Similarly, plants cultured in bioregenerative life support systems require protection from harmful solar UV. For these cases, the development of biological UV dosimeters complementary to physical UV monitoring systems is recommended (Rettberg and Horneck, 1999).

Protection from Martian Surface Dust

Surface dust is considered as one of the dominant environmental hazards affecting robotic and human activities by contaminating moving parts, environmental control components, optical sensors, windows, human organs etc. In order to assess its impact on humans and equipment, it is recommended to conduct terrestrial simulations of surface dust contamination to further improve engineering design, to conduct *in-situ* experiments to verify and refine engineering design parameters related to dust contamination, and to conduct biomedical studies to determine guidelines for habitat contamination. A first approach to shed light into the chemical and environmental hazards that may confront future planetary explorers has been planned by the Mars Environmental Compatibility Assessment (MECA) to be installed in one of the future Martian satellites (Keller *et al.* 2000). During dust storms, the attenuation of the total influx of solar radiation, especially in the visible range, may reach a reduction up to a factor of 50 (Smith *et al.* 2002) which will have a serious impact on the *in-situ* operations, but also on human health and psychology.

Planetary Protection Issues: Protection of Humans from a Putative Martian Biota

The planetary protection policy accepted as an official COSPAR policy provides guidelines in order to prevent both, forward and back contamination: on the one hand the policy requires to protect the Martian environment from contamination by terrestrial microbes and organics in order to maintain its pristine state, on the other hand since it cannot be excluded that putative Martian microorganisms might exist that may be harmful to human health, a rigorous quarantine test program is required for any sample return mission which has to happen before humans land on Mars (DeVincenzi, 1992; Rummel, 1995; Rummel and Meyer, 1996). As long as the risks of potential hazards to humans are not ruled out, any attempts should be made to isolate the human operator from direct contact with Martian material. The needs for implementing appropriate planetary protection guidelines, especially for missions with long stay times on the Martian surface has been discussed in more detail by DeVincenzi and Klein (2000).

HUMEX Study on the Survivability and Adaptation of Humans to Long-Duration Interplanetary and Planetary Environments

Other environmental stressors include the reduced gravity and the lack of essential prerequisites for supporting life, such as a sufficient atmosphere, water and moderate temperatures. These risks have been especially considered within an ESA Study on the Survivability and Adaptation of Humans to Long-Duration Interplanetary and Planetary Environments "HUMEX" (Horneck *et al.* 2002). The overall objectives of this study are:

- to define reference scenarios for a European participation in human exploration and to estimate their influence on the Life Sciences and Life Support requirements;
- for selected mission scenarios, to critically assess the limiting factors for human health, wellbeing, and performance with respect to long-term reduced gravity and radiation exposure, and to recommend relevant countermeasures;
- for selected mission scenarios, to critically assess the potential of Advanced Life Support Developments and to propose a European strategy including terrestrial applications;
- to critically assess the feasibility of existing facilities and technologies on ground and in space as test beds in preparation for human exploratory missions and to develop a test plan for ground and ISS campaigns;
- to develop a roadmap for a future European strategy towards human exploratory missions, including preparatory activities and terrestrial applications and benefits.

Within the HUMEX study, the following most critical items have been identified that need special attention for a safe human missions to Mars: (i) solar particle events; (ii) very long microgravity periods during interplane-

tary transfer; (iii) very high g-loads during landing on Mars, especially in case of aerobraking; (iv) mission interruption and rapid return impossible; (v) long delays up to 45 min in communications; and (vi) problems may arise in view of in crew size and composition including psychological issues.

PROTECTION OF THE PRISTINE ENVIRONMENT OF MARS FROM HARMFUL HUMAN INFLUENCES

Planetary Protection Issues: Preventing Contamination of Mars

As mentioned above, the risks of contamination involved in the presence of humans on Mars are threefold: (i) the risks to the crew from Martian microbes (if any exist), (ii) the risk to life on Earth via returned Martian samples (accidentally or deliberately brought back to Earth), and (iii) the risk to Mars from imported terrestrial microorganisms. For the latter case, the planetary protection protocols as accepted by COSPAR require the following measures: all vehicles landing on Mars and their equipment should be assembled in a clean room, they should be sterilized by appropriate procedures to achieve "Viking-like" microbial load reduction requirements, and recontamination should be prevented by enclosing the sterilized lander with its equipment in a bioshield (DeVincenzi, 1992). These requirements reflect the need to prevent contamination of the Martian surface with terrestrial microorganisms – which would jeopardize the chance to detect life forms indigenous to Mars – and thereby preserving the integrity of the "search for signatures of life experiments" as part of the scientific payload.

However, these requirements can only be met with robotic missions to Mars. The scenario changes when humans are involved in the mission. Since humans carry vast amounts of microbes required to sustain important body functions, Mars will become inevitably contaminated with terrestrial microorganisms as soon as humans arrive on its surface. Although the surface of Mars seems to be very hostile to microbial life (Klein, 1992), it cannot be excluded that some microorganisms accidentally imported may find protective ecological niches where they could survive or even metabolize, grow, and eventually propagate. Having this in mind, the ESA Exobiology Team stressed the vital importance of a substantial series of robotic missions to precede the human mission to Mars in order to carry out the essential exploratory search for life by *in situ* measurements at selected sites (Brack et al. 1999).

Protection of Unique Sites of Scientific, Historical and Ethical Value

As a consequence of human activities on its surface, the planetary environment parameters of Mars may change with time. This may become especially severe if natural resources are utilized in large scales. Therefore, a systematic recording of the environment should be initiated from the first human entry on the planet. Especially the natural release of gases may provide information about the interior structure and may also be of use for establishing a permanent human base. Such natural gas releases may be detectable now, but could become difficult to detect in the presence of intense exploration. Therefore, a search for natural transient gas releases should be done from orbiters or by use of surface sensors before the establishment of a permanent human settlement.

A human mission to Mars and follow-on activities may also be considered as invading process disturbing the Martian pristine environment. Therefore, before humans will enter the extraterrestrial environment, the legal issues to preserve this unique environment need to be solved. In this connection, the Antarctic treaty may serve as a model example paving the path for a Martian agreement.

Mars possesses already unique sites of historical or scientific value, such as the landing sites of the Martian robotic missions Viking 1 and 2, and of Pathfinder with its rover Sojourner. More of such sites will hopefully follow in the future. In addition, other locations may be geologically unique or have unique features of high scientific value. Such locations should be preserved for future scientific evaluation.

It is very likely that not all environmental effects to the Martian environment from human activities on its surface can be anticipated in advance. Therefore records of human activities on the planetary surface should be maintained in sufficient detail that future scientific experimenters can determine whether environmental modifications have resulted from explorations.

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