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Space Policy 20 (2004) 217–225
Space Policy
www.elsevier.com/locate/spacepol

Mars through the looking glass: an interdisciplinary analysis of forward and backward contamination

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Abstract

The exploration of the planet Mars represents a significant milestone in humanity's exploration of the Universe. In the quest to better explore and understand Mars, issues of forward and backward contamination are particularly pertinent. This paper provides an interdisciplinary analysis of forward and backward contamination. Its substantive material reflects the scientific and technical concerns through the looking glass of legal and policy issues, and vice versa. The paper critically surveys contamination issues of current, nascent and proposed Mars missions from a scientific viewpoint. It then makes a comparative review of legal and policy mechanisms designed to protect against such contamination. It draws cross-linkages between the sciences and the law in this area. The paper then delineates a suggested interdisciplinary framework to protect against forward and backward contamination. This framework is based on co-operation between the various nations undertaking Mars missions, as well as between the various fields of expertise. It highlights the importance of an interdisciplinary overview in the implementation of measures protecting against forward and backward contamination. Strategies on the implementation of these measures are also outlined.

1. Introduction and context

1.1. Mars exploration

The early histories of Mars and Earth clearly show similarities [1,2]. Even if the Martian surface is a fairly cold and dry place today (the average mean temperature at solid surface is about 210 K [3] with diurnal variations of at least 15° [4,5]), there is conclusive geomorphological evidence [6–8] that liquid water in the forms of rivers and persistent standing bodies was present during the Noachian Epoch (the early heavy bombardment period, which was characterized by high meteor and comet impact rates) and the later Hesperian Period [9]. Even if today the low temperatures, dry conditions and merciless exposure to UV radiation [10,11] would make it fairly difficult for even the hardier of unicellular organisms to survive, the permanently frozen layers of soil underneath the surface can provide a less hostile environment and could therefore represent a possible biological niche for Martian biota [12].

Mars is considered one of the prime targets in our Solar System for the search of extraterrestrial biota. An international fleet of four spacecraft (the two NASA Mars Exploration Rovers [13] MER-A and MER-B, the European Mars Express spacecraft with its Beagle2 lander [14] and the Japanese Nozomi orbiter [15]) have all recently visited, or are visiting, Mars, with varying degrees of success. MER-A, MER-B and the ESA Beagle2 probe were designed to land on Mars in order to perform an extensive in situ analysis of Martian soil and to look for fossil and possibly extant Martian biota.

Since 1960, a large number of unmanned spacecraft have been sent to Mars. So far only three landers have achieved a soft landing on the surface of the red planet: the USSR's Mars 3 orbiter reached Mars orbit in 1974 and landed the same day between the Electris and Phaetontis regions. The lander failed after 110 s after transmitting a small portion of a picture. The combined US orbiter/lander Viking 1 and 2 spacecraft reached Mars orbit in June and August 1976 and landed in

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0265-9646/$ - see front matter © 2004 Published by Elsevier Ltd.
doi:10.1016/j.spacepol.2004.06.008

Chryse Planitia and Utopia Planitia, respectively [16]. Both Viking missions were extremely successful. Each lander was equipped with one biology laboratory with three different experiments designed to search for evidence of living micro-organisms in material sampled from the Martian surface and were therefore the first to carry out an in situ search for extraterrestrial life on a planet [17]. Three landers have so far not achieved a soft Mars landing and crashed onto the surface: the two Soviet spacecraft Mars 2 and Mars 6 in 1971 and 1974, respectively, and the NASA Mars Polar Lander in 1998 [18].

1.2. History of contamination problems

Implementation of planetary protection (PP) measures for the Viking mission in 1975–1976 presented a significant challenge compared to previous unmanned missions. For one thing, the landers were planned to contact the Martian surface; for another, pre-Viking estimates of the probability of growth of terrestrial organisms was considered to be higher for Mars than for the Moon or other extraterrestrial bodies in the solar system [19]. In addition, there were instruments aboard each lander designed to search for metabolic activity in surface samples that might contain Martian micro-organisms. This imposed the need to prevent any terrestrial "hitchhiker" organisms from confusing the life detection experiments. In keeping with the statistical approach to PP utilized at that time, NASA issued probability parameters for use by Viking mission planners for both the orbiter and landers [20]. The more stringent probability parameters were assigned for the landers and included estimates of the Probability P of (1) survival of organisms in space vacuum and temperature; (2) survival of space UV flux; (3) arrival of organisms at Mars; (4) surviving atmospheric entry at Mars; (5) release of organisms from the landers; and (6) growth and proliferation of terrestrial micro-organisms on Mars. Finally, in arriving at the overall probability of contaminating Mars, these parameters were to be multiplied by the estimated microbial load on the spacecraft at launch [20,21]. Each Viking spacecraft was supposed to meet the criterion of 10^{-3} or less for the probability (P) of contaminating Mars. Because the spacecraft were known to carry a significant bioload, it was clear from the outset that the Viking landers would need to undergo active bioload reduction. After experimental tests of various techniques, dry-heat "sterilization" of the landers was eventually selected as the method for effective bioload reduction.

NASA made substantial revisions to its original PP policies, taking into account new information acquired by US and Soviet spacecraft missions to Venus and Mars in the intervening years [22–25]. In 1984, a revised PP policy was approved at the XXV Committee on Space Research (COSPAR) Meeting in Graz, Austria [26]. The quantitative, probabilistic methods that had been used for the Viking missions were replaced instead with PP requirements based upon the type of mission (flyby, orbiter, probe, lander) to be flown as well as the target planet. Five categories were defined, which spanned a range of mission/target combinations and corresponding PP requirements. To summarize:

- Category I missions include any mission to a target planet which is not of direct interest for understanding the process of chemical evolution. Protection of such planets is not warranted and no requirements are imposed.
- Category II missions comprise all missions to target planets where there is significant interest relative to chemical exploration, but there is only a remote chance that contamination could jeopardize future exploration. In this case, the only requirements are for appropriate documentation.
- Category III includes certain types of missions (flybys, orbiters) to a planet of exobiological interest for which contamination could likely jeopardize future biological exploration. The requirements for this type of mission include impact avoidance and contamination control. All orbiter spacecraft and flyby modules should be assembled in clean rooms of Class 100,000 or better. The probability of impact for launch vehicles must not exceed 10^{-5} and the probability of impact for a flyby module must not exceed 10^{-3}.
- Category IV includes probe and lander missions to target planets of chemical evolution and/or origin of life interest for which scientific opinion provides a significant chance of contamination which could jeopardize future biological experiments.
- Category V includes all sample return missions. The concern for these missions is the protection of the terrestrial system, the Earth and the Moon. Some guidelines have been proposed for this Category21, 26, 27 and will be discussed below.

PP guidelines specifically for Mars missions have been recently reviewed by the Space Studies Board (SSB) of the US National Research Council [28]. The SSB concluded that, although contamination of the Martian environment by growth of terrestrial organisms was not a significant hazard, terrestrial contamination was a significant threat to interpretation of experiments designed to search for extant or fossil Martian micro-organisms. Therefore, the SSB recommended that bioload reduction on all lander missions to Mars continue to be addressed, but that the level of contamination control be tied to specific mission objectives. Category

IV missions were therefore subdivided into two subgroups [29,30]:

- Category IVa missions comprising lander systems not carrying instruments for the investigation of extant Martian life. These missions are restricted to a biological burden no greater than Viking lander pre-sterilization levels.
- Category IVb missions comprising lander systems with specific life detection instrumentation. In that case the landers are recommended to have at least a Viking post-sterilization biological burden level. Note that the Viking Lander Capsules were each subjected to a terminal dry heat sterilization cycle of approximately 30 h at a heating temperature of 110°C in order to achieve 112°C at the coldest point in the landers [31].

In the 1960s, when the USSR mounted several unmanned missions to Venus and Mars, information about their missions was fragmentary or available mainly from newspaper reports. Several of these missions probably impacted Venus and Mars, some accidentally and others by design, thereby almost certainly depositing terrestrial organisms on Venus and Mars as a consequence [32]. Numerous statements from the Soviets during this period asserted that their missions were in compliance with COSPAR PP recommendations. For the Mars 2 and Mars 3 Soviet missions in 1971, which both deposited landing capsules on the Martian surface, it was claimed that a combination of measures was applied to safeguard against deposition of terrestrial organisms on Mars.

More recently, for the Mars '96 mission the Russians and their associates conformed to the new COSPAR guidelines. The mission comprised one orbiter, two autonomous small stations which would land on the surface, and two penetrators which would penetrate into the Martian soil [33]. Unfortunately the launcher experienced an on-orbit failure and re-entered the Earth's atmosphere above the South Pacific ocean (simulated trajectory) on 17 November 1996. The Mars '96 orbiter did not need any implementation of sterilization procedures because the probability of spacecraft crash did not exceed 10^{-5} and its orbit was in accordance with quarantine requirements (orbit lifetime with 0.9999 confidence for the first 20 years and 0.95 confidence during the next 20 years). For the Mars '96 small stations, different methods were used and especially for the French and Finnish payload, hydrogen peroxide gas plasma sterilization was applied [34].

1.3. Legal history of protection against contamination

Environmental provision within the existing *corpus juris spatialis* is minimal. International environmental law and international space law rank as the two newest developing areas of international law. International responsibility and liability in space activities is not generally envisaged to include damage to the outer space environment. Article VII of the 1967 Outer Space Treaty [35], which is further elaborated upon in Articles 2–4 of the 1972 Liability convention [36], clearly invokes international liability for personal injury to persons and damage to property caused by space objects. Damage to the environment caused by space objects or by contamination did not figure in the drafters' considerations [37].

There are only two clear provisions relating to contamination in treaty law concerning outer space. Article IX of the Outer Space Treaty obliges states parties to "pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination" [38]. This Article imposed international obligations on all state parties to protect and preserve the environmental integrity of outer space and celestial bodies such as Mars. However, the broad scope of this Article was severely curtailed by its imposition on states parties to take only appropriate measures, where necessary, to avoid harmful contamination [39]. The Outer Space Treaty does not specify the circumstances in which such measures would be necessary or appropriate [40]. This provision is not self-executing. It has, however, led to additional promulgation of guidelines, such as those by COSPAR, as mentioned above.

Further, Article 7(1) of the 1979 Moon Agreement [41] provides that in "exploring and using the Moon, States Parties shall take measures to prevent the disruption of the existing balance of its environment, whether by introducing adverse changes in that environment, by its harmful contamination through the introduction of extraenvironmental material or otherwise".

Other more general Articles in the Outer Space Treaty supplement these two provisions. Article I, e.g. provides that the "exploration and use of outer space, including the moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of scientific or economic development, and shall be the province of all Mankind". The protection and preservation of outer space and celestial bodies such as Mars is properly an extension of the "province of Mankind" principle. Further, the contamination of Mars would jeopardize the rights of all countries to use and explore outer space.

These provisions are vague and left open to legal interpretation. There is no definition as to what constitutes "harmful" contamination, or an "adverse" change to the environment. Apart from such definitional problems, there are other matters of law. The Moon Agreement has been ratified by only nine States as of

2003, and is considered to be little more than a dead letter [42]. The Outer Space Treaty, however, has better legal standing. Having been ratified or acceded to by the majority of states, including the major spacefaring nations, it is generally considered the Magna Carta of international space law. More crucially, because of the consistent and widespread international support for its fundamental tenets, and the fact that it was based on an earlier 1963 Declaration adopted by consensus in the United Nations General Assembly [43], the principles enshrined in the Outer Space Treaty have taken on the status of customary international law [44]. They are therefore binding on all states, even those that have neither signed nor ratified the Outer Space Treaty.

This is of special significance. Article III of the Outer Space treaty provides that the exploration and use of outer space is to be carried out in accordance with international law. It thus allows our inquiry to be carried over to the principles of general international law, and in particular, the principles of international environmental law.

The evolving corpus of international environmental law is a large and complicated one [45]. There are now many international instruments that deal with questions of the environment [46]. For our purposes, the work of the International Law Commission (ILC) on state responsibility is of particular interest. The ILC's 1996 Draft Articles on State Responsibility [47] deal with the question of duties in respect of areas not under national jurisdiction. This is of particular significance since Article II of the Outer Space Treaty places outer space, including the Moon and other celestial bodies such as Mars, beyond the limits of national jurisdiction. In this respect, Draft Article 19(2) provides that the breach of an obligation "so essential for the protection of the fundamental interests of the international community that its breach is recognized as a crime by that community as a whole constitutes an international crime". Draft Article 19(3)(d) further indicates that such an international crime could occur through breach of international obligations "such as those prohibiting massive pollution of the atmosphere or of the seas". Seen in this light, it is a plausible argument that the contamination of the outer space environment, including celestial bodies such as Mars, could be considered an international crime against the fundamental interests of the international community.

In 1972, the United Nations convened a Conference on the Human Environment in Stockholm. Principle 21 of the Declaration of the UN Conference on the Human Environment states:

> States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental policies, and the responsibility to ensure that activities within their jurisdiction and control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction.

At Stockholm, therefore, consideration was given to the contamination of areas "beyond the limits of national jurisdiction", which includes outer space and celestial bodies such as Mars. Principle 21 of the Stockholm Declaration was reinforced by Principle 2 of the 1992 Rio Declaration.

Indeed, the international obligation to protect the environment from contamination has been recognized as a matter of law. The International Court of Justice has expressly held in its 1996 Advisory Opinion on the Legality of Nuclear Weapons [48] and its 1997 decision in the Gabcikovo-Nagymaros Case that it attaches "great significance to respect for the environment, not only for States but also for the whole of Mankind" [49]. It is therefore arguable that there exists at international law an obligation on spacefaring states to take measures to avoid the contamination of outer space, including the Moon and other celestial bodies such as Mars.

1.4. Importance of developing a legal framework

The enunciation of the legal framework to guard against the contamination of celestial bodies such as Mars is crucial for at least two reasons.

- *Legal Vacuum for the Protection of the Outer Space Environment*: There is a very limited international legal framework specifically dealing with the protection of the environment in outer space. Consequently, outer space and celestial bodies are open to use (and possibly abuse) by all states and their nationals. A complete enunciation of the legal standards applicable is needed. Such standards are necessary as outer space and celestial bodies such as Mars become increasingly available for use and exploration.
- *Elaboration of Principles of International Law*: This legal framework could serve to elaborate on the principles of international environmental law as applicable to outer space. States have come to accept the legal significance and customary international law status of UN General Assembly Resolutions concerning the protection of the environment [50]. These resolutions are authoritative interpretations of the UN Charter, contributing to the formation of customary international law. A detailed and unequivocal UN statement of the applicable law is crucial. This will ensure that the use and exploration of outer space, including celestial bodies such as Mars, remains in conformity with international environmental law.

2. The significance of protection against contamination: scientific viewpoints

UN Treaties articles relevant to contamination are very general and it is therefore crucial to build up a good understanding and provide ethically and scientifically consistent reasoning why a PP policy for Mars is important. The following criteria can serve as a basis [29]:

- *Ethical*: the environment of Mars must be protected from any biocontamination by terrestrial microorganisms in order to avoid any harmful interference with putative local life or the environmental conditions that could lead to the apparition of a future life form. Planets having an exobiological interest must also be protected in order to allow the concerned community to perform experiments on a "clean" planet, i.e. one not contaminated by any other mission focused on other scientific topics.
- *Scientific*: the exobiological experimentation results must be ensured in order to avoid any misinterpretation that would then lead to an inappropriate adaption of a future PP policy. This requires avoiding both "false positive" (e.g. the discovery of traces of life on a Mars sample, which is, however, not indigenous to Mars) and "false negative" results (e.g. the non-discovery of a Martian life form on a sample because of its degradation as a result of poor preservation). To ensure this requirement the scientific integrity of returned materials has to be protected, which implies that the samples have to be preserved in a pristine and unaltered state, down to the isotopic composition level.
- *Safety*: the Earth's biosphere and the Moon must be protected against possible contamination by extraterrestrial forms of life, which could be included in return samples or carried by return probes or crews. This process is usually referred to as backcontamination".

Except in the case of the manned Apollo lunar missions, protection of Earth from back contamination was implied or only briefly mentioned in early NASA and COSPAR directives. Over the years, tentative PP guidelines for Mars sample Return (MSR) missions have been suggested [27] and a test protocol for detecting possible biohazards in Martian samples returned to Earth has been drafted [51]; however, no formal policy has been issued. The general guidelines for PP controls on an MSR mission should include [21]: (1) imposition of appropriate forward contamination measures; (2) verifiable containment of the Mars sample; (3) breaking the contact chain with the Martian surface before returning to Earth's biosphere; and (4) developing and implementing suitable protocols for quarantine testing and handling of the returned sample.

Containment of the sample will require sealing the sample in a container on the Mars surface in such a way that there is no release of contents during the return phase until the container is secured in a suitable containment facility. Although the conditions under which the sample is preserved inside the container have important scientific implications, the main objective of PP requirements is to ensure that the returned sample cannot escape to Earth's biosphere or pose any threat to it. Another PP concern is that extraneous Martian materials might be attached to the outer surface or crevices of the sample return capsule or Earth Return Vehicle when it lifts off the Martian surface. While unlikely, it is conceivable that organisms trapped in this material could survive exposure to the space vacuum and radiation and re-entry into Earth's atmosphere. There is the potential therefore that Earth's biosphere could be exposed to uncontained Martian materials [21].

3. Issues and solutions through an interdisciplinary perspective

Viewed quite simply, the need for containment in the space community is actually driven by two distinctly different emphases: on one hand, traditional biosafety and PP concerns, and on the other, sample protection and science considerations. The former emphasizes keeping materials in, while the latter emphasizes keeping contaminants out.

On top of the conflicting containment needs, the problem of PP is made even more difficult by spacecraft engineering demands, as all materials and mechanisms used during extraterrestrial sample return missions must work in the space environment of extremely low pressure, low and high temperatures, and prolonged, intense radiation. Robotic containment mechanisms must be reliable and their allowance for mass and power consumption will be extremely strict because of the size and weight restrictions imposed by spaceflight.

Apart from the engineering challenges scientists and space experts planning an MSR should be aware of the fact that they will be joined in the decision-making process by a vigilant public, the attentive mass media, and numerous government agencies providing oversight and review of any sample return proposal. It is almost certain that many legal, regulatory, institutional and decision-making issues will surface regardless of whether public opposition arises against the mission [52]. In the event of public disagreement over MSR plans, there are numerous federal, state and local laws that could be used to challenge mission decisions in court. Considering the potential for administrative delays, increased costs and missed launch windows could be the case if lengthy reviews or legal challenges occurred. It is therefore necessary to clarify these issues early in mission planning. In this regard, international space law has a distinctive role to play. Instead of an ex post facto judicial determination as to such contamination issues, it is submitted that international space law should take a leading role in defining and standardizing containment needs.

In setting international standards agreed upon by governments, scientists and policy makers, international space law can provide the crucible in which a negotiated outcome could be reached. Such an outcome should be enshrined into a Treaty regime complete with its own Protocols and detailed standards as to the necessary levels of PP to be undertaken by missions to Mars.

Apart from ensuring that such standards become binding on spacefaring states, the process of creating this regime would pave the way for international and interdisciplinary dialogue amongst the scientific, political, engineering and legal professions engaged in outer space. This in turn allows greater transparency and co-operation in ensuring the practical applicability and enforcement of such PP standards.

4. A proposed interdisciplinary framework

Although containment and handling of returned extraterrestrial materials will undoubtedly be complicated, it is not unprecedented. The conceptual and operational approaches used during the Apollo program are still applicable, albeit with considerable updating in technology, science and legal requirements. Furthermore, only about 500 g of Martian materials will be returned during the first sample return mission. As such, the sample receiving facilities for the Martian materials can be far less elaborate than the first Lunar Receiving Laboratory, which provided quarantine and containment for all returning astronauts, spacecraft, and lunar materials during its operation from 1969–1972 [53].

Additional information of relevance to the handling of potentially biohazardous extraterrestrial materials has been learned by analyzing containment and quarantine approaches used in the biomedical and genetic engineering sectors [54]. Finally, important design input for future extraterrestrial sample processing has also been learned from the handling of meteorites, lunar materials and interplanetary dust samples at Johnson Space Center over the past several decades. The on-going lessons learned from routine containment and analysis of diverse non-biological samples of extraterrestrial origin will be helpful in many ways, especially in areas related to sample characterization, preservation, cleanliness, and sterilization techniques.

It is essential to synthesize the multidisciplinary constituents of Mars missions in any PP scheme. The objective of this section is to delineate the fundamental prerequisites to combine scientific, engineering and legal elements. Ultimately, unless each group becomes acquainted with the other's discipline, there is the possibility that lawyers will make suggestions that are technically unworkable, while scientists and engineers propose illegal designs. A further task is to harmonize economic and political factors. Since the technology in this area is fast-moving, it is incumbent upon the legal and political community to keep abreast of technical and scientific developments. This will ensure that international space law is realistically validated against the fabric of space exploration [55].

An interesting historical development that the field of international space law should take into account is the fact that the scientific community has established institutional policies addressing PP. Several of the more prominent policies include those established by NASA and various other national space agencies [23]. Further, as mentioned above, the international scientific community has also established voluntary PP policies under the auspices of COSPAR.

It is, however, especially in the implementation and enforcement stage of these policies that international space law can play a definitive role. Enforcement of such policies is generally easier at a national level. For example, NASA enforces its policy requirements through the authority of its policy officer. This officer has the authority to stop the launch of space missions that do not meet the required standards of NASA PP policies [24]. Additionally, since NASA has thus far been involved in almost all non-NASA solar system exploration missions, it effectively has a capability to enforce its PP standards on its partner entities as well [25].

It is submitted nevertheless that international space law can play a pivotal role in the international enforcement and standardization of PP norms. Through the auspices of the United Nations, in conjunction with COSPAR, a standardized framework and enforcement mechanism can be constructed that is both legally binding as well as scientifically and technically coherent. The advantages to this are that, first, there is dialogue between the international community as well as between the different fields involved in Mars missions; second, there is a threshold international protection standard that must be adhered to; and, third, these standards are legally binding and enforceable, and not merely voluntary.

The component parts of the whole project must be identified and assembled for comprehensive analysis according to the particular influence each exerts upon a successful outcome. This multidisciplinary venture involves additional elements from law, institutions and management; international relations; and scientific, engineering and technical expertise. There is agreement among the relevant fields on the objective of the exploration and use of Mars, but there is a range of views on the methods of attaining these goals. This need not deter the task of devising PP protocols via international space law. The international scientific and legal communities are both well placed to co-operate over the planning of PP protocols [56].

Considerable research is required to decide the methods of control that can be effective in ensuring compliance with any adopted treaty principles. Reporting information to the UN Secretary General has proven effective in some cases, such as disaster relief, contamination and pollution. In such cases, scientists and engineers want a central focal point for information [57]. It is this that automatically causes compliance because the objectives of the reporters and the people to whom they report are the same. However, it is necessary to ensure that such reporting requirements do not become impractical and disregarded. It is necessary to identify activities that can be effectively guided or regulated in accordance with agreed objectives and those that require expertise for operational effectiveness [58].

5. Strategies for implementation

Recommendations for the implementation of this proposed interdisciplinary framework include

- Review of the Moon Agreement, especially its applicability to other celestial bodies such as Mars, should be placed on the agendas of the United Nations Committee on the Peaceful Uses of Outer Space, with inputs based on a collaborative study between its Scientific and Technical Subcommittee and its Legal Subcommittee [59].
- The Scientific–Legal Liaison Committee of the International Institute of Space Law (IISL) and the International Academy of Astronautics should set up a Working Group to frame a possible Protocol to the Outer Space Treaty. This Protocol should detail specific scientific standards, as adapted from the COSPAR recommendations and updated for present and future technologies and missions, and be framed into a binding legal regime. The Protocol should also provide for an implementation and enforcement mechanism, through a multidisciplinary organization, to ensure the implementation of such PP standards. There should be a review mechanism for the Protocol with five-year gap periods to ensure that the standards remain practical and updated. The Protocol should be presented, and hopefully adopted through consensus, by the United Nations General Assembly. This will provide a declaratory framework upon which a binding treaty regime can be established.
- Professional scientific organizations such as COSPAR should work with legal organizations such as the ILC or the IISL in widening the compass of their conferences to incorporate all aspects of PP and the exploration and use of Mars and other celestial bodies. Potential intercourse between disciplines should be distinguished and exploited [60].
- Individual nations and groupings of nations (such as the European Space Agency) should use their executive and legislative institutions to keep apprised of evolution in space exploration and technology. Progressive focus should be placed on harmonizing disparate components of Mars missions to ensure that PP standards are not jeopardized in the pursuit of the "better, cheaper, faster" philosophy.
- The United Nations Committee on the Peaceful Uses of Outer Space should establish a central research institution that would undertake responsibility for identifying and integrating all multidisciplinary elements involved in Mars exploration. Research and development should occur over a prolonged period during which both technology and personnel will evolve. An institutional archive should be established to assist future mission planning and PP standardization [61].

6. Conclusion

The race for the preservation of the Martian environment is an inverse race for time. Once the environment on Mars has been contaminated, there is no avenue for restoring the status quo ante. The pristine environment of Mars must not be lost forever to scientific investigation and natural evolution through careless contamination. The formulation of a workable interdisciplinary framework for the protection of the environment on Mars will serve not only to ensure the salvation of the Red Planet. It will also serve as the first step towards a comprehensive workable framework for the protection of the outer space environment and other celestial bodies.

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