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White Cosmic Study on Global Human Mars System Missions Exploration

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ABSTRACT

The International Academy of Astronautics has set up a Study Group (SG 3.16) to produce a Cosmic Study dealing with a global Human Mars Mission. The first results of this work are summarized in a White Cosmic Study to be presented at the Heads of Space Agencies meeting in Washington D.C. (USA) in January 2014.

The motivations of a global human Mars mission are first expounded. Attention is then directed to the human and technical aspects of such a complex mission and on the research still needed to bring all the relevant technology to the required technology readiness level. Aspects related to the international collaboration needed to perform what is a really global, affordable and safe mission are then dealt with. The study is completed by a number of recommendations

1. INTRODUCTION

Human missions to Mars have been studied by Space agencies in various countries (United States, Soviet Union/Russia, European Space Agency) over the past decades. However, a cooperative Human Mars Mission framework including, but not limited to, requirements and technologies, is still missing.

The International Academy of Astronautics has set up a Study Group (SG 3.16) to deal with this subject, with the goal of identifying, assessing and synthesizing a global set of goals with their related criteria and requirements for future human exploration of the Mars system and establishing technology opportunities and roadmaps in the context of promising cooperative exploration scenarios. The composition of the IAA study group is reported in Appendix 1.

The Cosmic Study prepared by this team is expected in 2015 but a White Paper summarizing the provisional conclusions reached after the first year is scheduled to be presented at the Heads of Space Agencies meeting in Washington D.C. (USA) in January 2014.

The IAA is fully aware of the remarkable work conducted for many years by national and regional space agencies in the framework of the International Space Exploration Coordination Group (ISECG), which has established, and is regularly updating, the Global Exploration Roadmap. While agreeing with the content of this roadmap and with its associated exhaustive and progressive list of objectives (that include missions to the Moon, the asteroids and Mars), the preliminary conclusions of SG 3.16 stress the importance of Human Mars Exploration as a global international enterprise.

This goal can be pursued in a spirit similar to that which animated the ISS program, as a large-scale international effort, able to federate the capabilities of many countries and regions represented by their space agencies, so as to realize an ambitious project with an obvious scientific, cultural and cultural value.

This preliminary conclusion implies that exploration is by nature a progressive effort and that all its destinations can be considered as stepping stones toward further, more ambitious, goals. Intermediate destinations – the Moon, the Lagrange points in the Earth-Moon system, the asteroids – can be viewed as intermediate steps toward Mars.

In this light it is possible to outline an international program, involving not only the countries that now participate in the ISS program plus the other current spacefaring countries, but also a number of other countries, in particular developing countries, that can find a role in this global enterprise. This enterprise can follow the existing dynamic of international human spaceflight, giving human exploration its real meaning, through exploring the most scientifically interesting places in the Solar System with all the capabilities linked with the presence of human researchers. The long term perspective is establishing permanent bases on other celestial bodies and moving towards the creation of human settlements away from the Earth.

From these different points of view, Mars exploration has unique advantages and is a natural priority, at least within the perspective of forthcoming efforts in the realm of global international human spaceflight.

This cosmic study is not the only effort in this direction performed by the IAA: other study groups are dealing with specific problems that are relevant for the goals here studied, like for instance planetary protection issues, the establishment of cryogenic propellant depots, etc. The synergies between the various study groups is self-evident.

2. WHAT KIND OF MARS HUMAN MISSION?

Since the beginning of the space age in 1957, human spaceflight has been the most visible and fascinating part of space activities. It started in a political context (the cold war) favoring large-scale space competition and a race to the Moon in the 1960s and 1970s between the two super-powers of the time, the United States and the Soviet Union. The highlight of this competitive period was the landing of humans on the Moon in 1969, as a result of the U.S. *Apollo* program. However the exploration drive, that was fundamental in the first decade of human spaceflight, lost its dynamic in the following years, with missions limited to low Earth orbit (Space Shuttle, space stations). This loss was accompanied by an important change: international cooperation instead of competition became the main political rationale for human spaceflight, leading to the International Space Station (ISS) program as it exists today, with six major partners: Canada, Europe, Japan, Russia and the United States.

Now that the ISS is completed and working, the question for the international space community is: what will be the next steps in international human spaceflight cooperation? Should it be a continuation, possibly with a broader international base, of current human activities in LEO, focused on sciences in microgravity or would it be possible, at last, to resume the human exploration drive of the nascent space age, but to do this within the framework of international cooperation which was so successful with the ISS?

The Global Exploration Roadmap by the ISECG mentions three destinations for human exploration, namely the Moon, the Asteroids and Mars. Among these, Mars is best suited to represent the goal of such a global effort of international cooperation. With their large inherent importance within scientific, technological, economical and other regimes, the first two destinations can be seen to constitute intermediate goals (i.e. they are essential stepping stones on the way to Mars).

However, further to the stepping stones to Mars, it is possible to define a number of different approaches to proceeding there in the order of their complexity:

- 1) A flyby mission
- 2) A mission to one of the satellites of Mars (from where astronauts may tele-operate devices on the surface of the planet)
- 3) A short stay mission (a sort of flag-and-footprint mission)
- 4) A long stay mission, with limited scientific operability
- 5) A long stay mission, with full scientific and exploration capabilities
- 6) A long stay mission, intended as the first step toward more ambitious objectives like colonization.

A decision as to which approach to follow is a determinant factor in choosing required technologies and in evaluating the feasibility and the affordability of the whole plan.

3. MOTIVATIONS

The reason to consider a human Mars mission as a unique objective resides in its vision and value for internat-

ional scientific and technical cooperation in the coming decades, and it combines a number of different rationales, some of which are described below in some detail.

- **Political interest.** Cooperation on large-scale scientific and technological programs has become a major trend in the world of the beginning of the 21st century. Outer space is, however, a domain in which international cooperation has flourished at an incomparable level regionally (notably through ESA in Europe) and globally, particularly with the ISS program, which is by far the largest technological cooperation ever undertaken. From this point of view, the Mars destination has unique advantages. The red planet has been considered since the 19th century to be a very special place, which could harbor life, and could become a second home planet for humans.
- **Scientific value.** Even if the scientific goals of Mars exploration may not, by themselves, justify totally the sharp increase in resources required when switching robotic exploration to human exploration, for the time being science remains the basic driver of the program's operational goals and the scientific community is the prime partner in this endeavor. It is thus of the utmost importance to build a program that takes into account the wishes of scientists regarding investigations. It is also necessary to demonstrate that a human presence will be a powerful enhancer of robotic productivity.
- **Contribution to innovation and economic development.** A large-scale techno-scientific program, like a human expedition to Mars, venturing into the unexplored and to the limits of our know-how, constitutes one of the most powerful tools in the hands of governments to push forward their nation's innovation capabilities and economy.
- **Societal aspects.** At a time when globalization leads to an accelerated diffusion of know-how and activities, the strategic character of innovation and of entrepreneurship is more than ever recognized. It is also required to attract an appropriate flux of students towards techno-scientific jobs to augment the creative workforce that will innovate and create business. Space exploration, and in particular human missions, can attract the attention of the public over a long time period and have a large impact on the collective imagination.
- **Cross-cultural aspects** In a situation like the present one of growing international and inter-cultural frictions, it is of vital importance to find subjects that can give rise to a broad common interest among countries and cultures, and thereby enable significant cooperation ventures to be pursued that establish bridges between peoples of different origins and civilizations.

4. MISSION PLANNING

This section is the longest in the whole report. Human missions to Mars have been characterized and studied even before the beginning of the space age and are often considered as “the” long-term goal of human spaceflight. The number of studies regarding missions to Mars is large. The question is thus: why such an interest and an investment in architecture and mission studies has not yet been transformed into real programs with hardware development and schedules? The main reason is certainly the size, duration and cost of the needed effort. However, are high costs really necessary? Is it not possible to design and plan a less expensive mission while maintaining fully its scientific and emblematic value? Hence, the primary focus of the present part of the study is affordability, without which no serious attempt can be made. Affordability must be achieved without compromising safety and without jeopardizing the possibility of attaining the goals outlined in Section 3.

4.1 Human factors

As a first point it must be clearly stated that a human mission must be centered on the fact that human beings are onboard and that crew safety and well-being is of fundamental concern. Human issues are thus dealt with first. These issues centre around three stressors: low gravity, radiation, and psychological and cultural factors. These stressors in turn affect human physiology, cognition, and individual and crew psychosocial status.

Low gravity and exposure to radiation are first considered in some detail and mitigation strategies are taken into account. For the issue of gravity, the main point is: how much gravity is sufficient? We still cannot answer this question and we do not know how humans can live in Mars gravity for long periods of time.

The amount of radiation (from Galactic Cosmic Radiation/GCR and Solar Energetic Particles/SEPs) is by no means trivial. The effect of galactic cosmic radiation at the Martian surface during a 30-day (short) stay during solar cycle minimum was estimated to be acceptable. However, for longer stays the situation becomes gradually worse and would be exacerbated by the occurrence of a hard spectrum SEP.

Strategies to reduce the total mission dose predicted to be incurred during a mission to Mars include studies to optimize the launch window and the on-going development of faster, more efficient, means of propulsion, since the risks due to radiation exposure as well as those accruing to zero-gravity can be reduced through implementing faster journey times. The use of advanced propulsion such as nuclear thermal or electric propulsion will both reduce exposure time and the likelihood of being caught in an extreme solar event. Also, the efficacy of using different kinds of shielding and investigation of possibilities to modify spacecraft design to provide better radiation protection for the crew are under consideration (for instance water walls).

Cognitive, psychological and cultural issues are next considered in some detail, and a first result is that the number of astronauts in the mission is a critical issue.

4.2. General considerations on affordability and risks

Two basic questions must be first addressed:

- 1) what is an affordable mission?
- 2) what are the main parameters affecting the choice of an affordable, reliable and safe architecture for transportation and planetary activities?

Even if the world has gone through a very difficult economic and financial crisis since 2008, and if some countries and regions are not yet out of this crisis, the fact is that global economic growth has overall been strong and sustained during the last decades, and that the relative effort (share of GDP) to conduct an ambitious human space mission, like landing a crew on the Moon, would be today much more “affordable” than in the 1960s, when the U.S. Apollo program was undertaken.

It is expected that the world economy will grow during the coming decades at a rate of about 3% per year and so will double during the 25 years foreseen to be required to land an international crew on Mars.

What is more, many emerging countries will continue to grow faster than the mean global growth rate, and will thus have the capability to join an international effort with significant means. Since the needed investment could be easier to cover by an increased number of countries with large economic strengths, the financial barrier of affordability will lower progressively.

4.3. Parameters affecting the selection of an affordable architecture for transportation and surface activities

Although the present study is not aimed at defining a new reference mission, it must deal with the possible configuration alternatives that may be chosen.

The choice of a reference architecture for a Human mission to Mars will be driven by the possible answers and technical solutions to basic relevant questions, including:

- How far can safety requirements be fulfilled? What is the risk level that can be accepted without hampering mission feasibility?
- What is the impact of radiation protection on the mission? Is there any showstopper linked to radiation exposure over a long period of time?
- Which is the most appropriate approach to counter microgravity effects on the human body? Is there any showstopper linked to microgravity exposure over a long period of time?
- What is the optimal compromise between mission duration (impact on, for example, consumables and radiation protection mass) and ΔV (impact on, for example, propellant mass)?
- What is the optimal time-sharing between time spent around Mars and time spent in interplanetary transfer, and what is the impact on mass?
- What are the mass critical components and what are the design possibilities to reduce the impact of these components on mission feasibility?
- Which are technologies worth investigating for a specific mission? - meaning that their implementation will result in significant benefits when the cost of developing them is viewed relative to the “mission case”?
- What is the best assembly strategy for a vehicle in LEO?

4.4. Transportation systems and mission architecture

The IAA Study Group considers that today, with sound principles, it is possible to design and implement a safe, resilient and affordable mission architecture, by taking into account the technological progress accomplished in space technologies during the last two decades. Some of the points discussed in detail are:

- Crew size. Considering the problem of the costs and risks of the mission, which are tightly linked to the IMLEO (Initial Mass in Low Earth Orbit), the number of astronauts should be reduced to a minimum, possibly 3, although quantifying this in a number is a highly controversial exercise. Candidate astronauts can have an extended training period and many tasks can be automatized. In general, human factor experts hold that a more appropriate crew number should be in the 5-7 range and even the fact that the mission is international may point towards a larger crew, so as to include representatives of a larger number of countries.
- Mars orbit insertion. There are 3 main options for Mars orbit insertion: aerocapture, aerobraking and propulsive braking. To reduce the size of the transport vehicle in a significant way, an aerocapture procedure for Mars orbit insertion is highly desirable for all vehicles but might prove to be unfeasible, in particular in the case of a large mission. As an alternative, the crew can be divided into two teams riding two small vehicles.
- Descent vehicles and EDL (Entry, Descent and Landing) strategies. The qualifications of EDL technologies and procedures might be long and expensive. For this reason, EDL is considered to be one of

the domains where efforts have to be made as a matter of priority to identify the most simple technologies and procedures available, even at the expense of imposing constraints on other parts of the mission. Splitting the payload into several parts should be regarded as a serious option

- Mars orbit to Earth orbit strategy The ERV (Earth Return Vehicle) is potentially the heaviest vehicle of the mission. To reduce its mass, three strategies can be followed: a propulsion system with an increased ISP, can bring more materials from the Martian surface and optimize the list of elements that are waiting in Mars orbit so as to proceed efficiently to assemble there two ERV modules. All modules and materials that are not required on the surface of Mars should stay in Mars orbit
- Tradeoff between chemical propulsion vs. nuclear propulsion. Much discussion was devoted to this issue. The main advantages of nuclear propulsion, thermal or electric, mentioned are basically:
 - A significant reduction of the IMLEO. Moreover, if the mission to Mars is considered as the first of a number of subsequent missions, the expenses needed to develop NTP or NEP can be considered to represent an investment and, once developed, nuclear propulsion would support easier exploration, by both humans and robots, of the whole Solar System.
 - If the problem of radiation during the months spent in space will ultimately prove to be a showstopper and a fast transit is required, nuclear propulsion would become the only possible choice.
 - Nuclear propulsion can allow a spacecraft to be designed with the capability to perform the whole two-way journey from Earth orbit to Earth orbit, with the added possibility of performing multiple journeys.

Among the advantages of xxx chemical propulsion were listed:

- It is not possible to just compare the specific impulse and there are many hidden problems with nuclear propulsion. A nuclear engine cannot be started in LEO and more propellant is required to get into orbit. A heavy radiation shield is required to minimize the radiation dose of the crew, which also has an impact on IMLEO.
- The main problem of nuclear propulsion, NTP or NEP, is the complexity and the required maturity of the systems. Several decades with expensive automatic precursor missions without clear scientific objectives can be required to develop all the systems and reach an acceptable maturity level.
- There exist several important options for chemical propulsion that were not examined in the last NASA DRA5 report which can potentially bring significant simplifications and IMLEO reductions.
- A stepwise approach, postponing the study of nuclear propulsion systems and the trade-off between NTP and NEP until after the first missions can be proposed.

4.5. The planetary infrastructure and vehicles

These basic elements, could be launched in two batches: one containing the surface habitat integrated with its landing vehicle and the second carrying a pressurized rover, a nuclear power plant and a small ISRU assembly. These elements shall land on the Mars surface before the arrival of the crew.

When dealing with astronaut permanence on the Mars surface, planetary protection is one of the main issues. Both forward (protection of the Mars environment from contamination from Earth) and backward (protection of astronauts, and finally of the Earth's environment from possible contamination from Mars) protection must be accurately studied and implemented.

- Surface Habitat. The Martian Surface Habitat shall be designed for long-term utilization with each human mission on the Mars surface lasting 1 year or more. The Surface Habitat shall: provide sufficient volume per crew member in a shirt sleeve environment and a breathable atmosphere; provide protection from the Martian environment and store resources (such as food, oxygen, water). Moreover, it shall provide means to perform science and other prescribed tasks. Due to the entry capsule constraints, the choice of an inflatable habitat is suggested. The amount of resources needed – food, water, gases – is highly affected by the mission duration and by the number of crew members and may be reduced if advanced Environment Control and Life Support (ECLSS) technologies are used. An additional level of loop closure can be achieved through the production of food and the recycling of solid waste.
- Power Plant. The quantity of energy required on the surface of the planet is by no means small. Apart from the life support system, large quantities of energy are required for in situ resource utilization, the rovers, the scientific equipment and all other devices required, including possibly a greenhouse to complement the life support system and the ISRU. It is likely that, to guarantee the continuous power production required to sustain crew surface operations, in particular in case of high power requirements, a nuclear power plant, possibly buried to ensure radiological protection, is likely to be required.
- ISRU plant. The use of in-situ resources will be a key driving factor to sustain human missions on Mars. The trade-off is complex because each option has an important impact on other parameters of the mission and at present there is no consensus as to preferred options. In-Situ Resource Utilization (ISRU) test beds will be landed on Mars before crew arrival to: process the atmospheric carbon dioxide; and extract oxygen to be breathed by the astronauts as well as used as oxidizer for the return vehicle. Beside oxygen, methane could also be extracted from the Martian atmosphere to propel the Mars Ascent Vehicle for the return of the crew to Earth.

- Pressurized Rover. The Pressurized Rover is regarded as a key element to sustain exploration by providing the crew with safe and robust mobility support, allowing them to explore larger areas in a shirt-sleeve environment. The Pressurized Rover is a very complex system because it has to meet habitability requirements similar to those required for the Martian Habitat, but with long-range mobility requirements. The rover might be based either on battery electric vehicle technology with recharging at the habitat power source, or on hydrogen-oxygen fuel cells, fuelled by the ISRU. A conventional, high TRL, technology based on the internal combustion engine might also be used. An unpressurised rover could be utilized for shorter EVA operations, to provide robotic support and to extend the mobility range of the crew.

5) PARTICIPANTS

Apart from the main objective of exploring Mars, one of the objectives of the human Mars mission is to combine as many established and emerging space powers as possible in a single ambitious space project, in a way similar to, but on an even wider scale, than was initiated to establish the largest technological cooperative program ever undertaken - the ISS.

The International Space Exploration Coordination Group (ISECG), with representatives from 14 Space Agencies, has initiated a non-binding coordination effort for preparing exploration of Humans beyond Earth. As already stated, the ISECG roadmap involves human exploration destinations that include the Moon, the asteroids and Mars. This roadmap is very relevant in the context of global human Mars exploration, both from the viewpoint of gaining the required experience for long-range human missions and for the internationalization of the exploration effort. The complementarity of the ISECG roadmap goals with those of a global human Mars mission is self-evident.

At present, the International Space Station program involves permanently 16 countries, with more than 60 countries now involved in its utilization. This participation must be widened for a global mission to Mars. Technological niches, scientific research in universities and research centers that can contribute to human space exploration exist in many of these countries. Many more countries could join a global human space exploration effort, at an affordable cost, and with an increased interest in Science and Technology for their citizens. The United Nations Office for Outer Space Application (UNOOSA) has an important role in fostering involvement of new and developing countries in human spaceflight activities. Apart from the participation of the space agencies, the direct participation of private organizations (both non-profit and commercial organizations) should also be discussed.

An important issue for the success of international missions is standardization of all mission hardware and software.

6) TIMEFRAME

The goal is to land a crew on Mars in a foreseeable time. However this goal cannot be reached in a single step. Intermediate steps would enable progressive development, testing and use of necessary systems:

- A Mars fly-by by a manned vehicle doubling as a Mars sample-return mission (a robotic lander would separate from the manned vehicle, make a pin-point landing close to a collecting rover, collect the samples, take-off and rendezvous with the manned vehicle that would take the samples back to Earth).
- A manned orbital mission to Phobos or Deimos, with remote operation of a large number of small rovers sent to the surface of Mars.
- A cargo mission to deliver to the surface of Mars the elements needed for the life of a future crew, enabling at the same time a test of the technologies to land heavy payloads on the planet.

Apart from these precursor missions directly dealing with Mars exploration, the study group stresses the importance of the other objectives included in the ISECG roadmap. Robotic and international human missions to the Moon and to the Asteroids are important stepping stones towards Mars. Also, they provide targets for future private commercial, exploitation and possibly exploration, missions, utilizing the capabilities developed through previous international collaborative efforts to explore the Moon and the Asteroids. A transfer of experience and technologies from these missions may reduce the cost, decrease the risks and make more affordable the human exploration of Mars.

It should be stressed that the IAA Group strongly suggests that the Human Mars mission is not a one-shot program, but only the first part of a project aiming at creating a permanent base on the Red planet in the second half of the 21st century, proceeding thereafter to settle Mars in the 23rd century and beyond.

7) CONCLUSIONS

A global Human Mars Mission should be considered relative to the capability it can provide of opening up the Solar System to human exploration, thereby transforming humankind into a spacefaring civilization. Such a mission should be truly global involving, together with the present spacefaring nations, emerging and developing nations. This will allow exploitation of all the technical and humanistic skills available and engage them.

Among the different possible approaches, only a long-stay mission, seen as the first step toward the creation of an outpost and then to the colonization of the planet, will satisfy the expectations raised by such an ambitious goal. There are many questions regarding both human factors and technical choices to be answered before a mission can be designed in detail. Research into these issues should start as soon as possible in a coordinated way, within the framework of a truly international research effort, so as to fulfill the specific aspects of human space exploration in accordance with the ISECG roadmap.

8) RECOMMENDATIONS

- 1) Define an International Mars reference mission scenario, with the involvement of Space Agencies/Industries, to agree on a preliminary technical baseline and the required technological decision milestones, for instance:
 - a. Nuclear thermal and nuclear electric propulsion
 - b. Zero-boil off technology for cryogenic propellant storage.
 - c. Nuclear power generator systems for both space and on-planet usage.
 - d. Passive or active radiation shielding technology.
 - e. Artificial gravity in space.
 - f. Effects of Mars gravity using large centrifuges or tethered spacecraft in orbit.
 - g. Aerocapture technologies for large payloads.
 - h. Life support systems, in particular regenerative ones.
 - i. In Situ Resources Utilization (ISRU) systems.
 - j. Exploration technologies, in particular astronaut robotic assistants, rovers, drillers, etc.
- 2) Set up a joint working group, IAA(SG3.6)/ISECG, to define in which of the Human Missions beyond Earth, defined in the ISECG roadmap, the technologies defined in the Mars reference mission (see recommendations 1) should be demonstrated, in order to reduce the risk and cost of the Global Mission to Mars. Demonstration projects, to be carried out by a variable group of countries will be defined to this end.
- 3) Foster the global involvement of countries, in particular of the emerging and developing countries, through existing bodies like ISECG, UNOOSA-HSTI, IAA, etc.
- 4) Improve the common knowledge of the human factors, as the most critical issue for the Mars mission.
- 5) Set-up a Human Spaceflight Virtual Institute, by IAA and with the participation of Space Agencies/Industries, to foster the exploitation of existing technologies, facilities and know-how available world-wide. This Institute will also facilitate the engagement of new and developing countries by identifying technological niches existing in these countries, as well as facilitating the exchange of information in many critical areas, such as human factors.

APPENDIX 1: COMPOSITION OF THE IAA SG 3.16

Chair:	Giancarlo Genta (Politecnico di Torino, Italy)
Co-Chair:	Alain Dupas (International Consultant, France)
Secretary:	Jean-Marc Salotti (Laboratoire de Science Cognitive, France)
Members: (in alphabetic order):	Kohtaro Matsumoto (JAXA, Japan)
Mauro Augelli (CNES, France)	Chris McKay (NASA, USA)
Andrew Aldrin (ULA, USA)	Susan McKenna-Lawlor (Space Technology Ireland Ltd. Ireland)
Nicolas Bérend (ONERA, France)	Ernst Messerschmid (Stuttgart U., Germany)
Giovanni Bignami (COSPAR)	Natalia Nikolaeva (Russia)
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Claudio Bruno (United Technol. Res. Cent., USA)	Maria Antonietta Perino (TASI, Italy)
John B. Charles (NASA, USA)	Viacheslav Petukhov (Russia)
Lin Chen (Lockheed Martin, USA)	Yury Razoumny (Russia)
Elisa Cliquet Moreno (CNES, France)	Pascal Renten (University of Stuttgart, Germany)
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