NASA's SPACE EXPLORATION PLANNING: THE ASTEROID MISSION AND THE STEP-WISE PATH TO MARS

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Within the U.S. space policy framework, NASA continues to advance its space exploration programs and plans to remain a world leader and valuable partner in space exploration. NASA's programs reflect the importance of human space exploration in the U.S. by focusing on the foundational capabilities and technologies which will ensure government investments continue to drive innovation and enable exciting missions as part of a step-wise path to Mars. NASA is focusing on developing these initial capabilities while collaboratively working with international partners to define a technically feasible and programmatically implementable strategy for deep space exploration. This paper summarizes this work and how NASA's approach to capability development enables a step-wise path to human exploration of Mars, with missions along the way providing the opportunity to infuse new technologies, advance capabilities, learn to manage the risks of operations in deep space while using the presence of the crew to explore, discover and inspire.

NASA is laying the groundwork for the partnerships necessary to explore beyond low-Earth orbit (LEO). In addition to the International Space Station enabling important learning related to long duration mission human health and performance, the heavy lift launcher Space Launch System (SLS) and the Orion crew vehicle are foundational capabilities under development for human missions beyond LEO. Initial Orion and SLS vehicles will enable near-term missions in the lunar vicinity and demonstrate capabilities and operations necessary for exploration missions further away from the relative safety of LEO. These missions also enable exploration of a near-Earth asteroid and the Moon, allowing the presence of the crew to engage the public in ways that further increase value to people on Earth. International and public-private partnerships will enable these early missions and ensure that human space exploration proceeds in a sustainable manner. This paper describes how the Asteroid Redirect Mission fits into the long term international context described in the Global Exploration Roadmap, released by space agencies participating in the International Space Exploration Coordination Group (August 2013). NASA welcomed the contribution of the January 2014 International Space Exploration Forum. The meeting of government representatives demonstrated the importance of international partnerships in exploring space and welcomed the work of space agencies on the Global Exploration Roadmap.

INTRODUCTION

NASA continues to advance its space exploration programs and plans to remain a world leader and valuable partner in space exploration. NASA's programs reflect the U.S. commitment to human space exploration by focusing on the foundational capabilities and technologies which will ensure government investments continue to drive innovation and enable exciting missions as part of a step-wise path to Mars. As evidenced by the Global Exploration Roadmap, Mars is the collective international horizon destination (Ref 1). Meeting the challenges associated with human missions to Mars is central to NASA's space exploration strategy. The long-term goal of human exploration of Mars informs robotic mission planning, technology development priorities, requirements for near-term human spaceflight capabilities, and activities onboard the International Space Station (ISS). Orion and Space Launch System (SLS) are currently under development, with Orion Exploration Flight Test-1 scheduled for this December. Technology advancements in high power, long life solar electric propulsion open new approaches for human exploration. These investments will enable humans

to leave low-Earth orbit (LEO) for the first time since Apollo and begin our sustainable path to Mars.

The journey to Mars has begun. A number of robotic spacecraft by several nations are gathering data or en-route to the red planet. These spacecraft are discovering knowledge that will prepare for future human missions. NASA's Mars 2020 mission has just completed instrument selection. The international science team is now gathering to discuss critical elements which inform development of the rover and its mission. Included in the science complement is the first investigation targeting in-situ resource utilization, which will contribute important knowledge preparing for future demonstrations of technologies to extract CO2 from the Mars atmosphere for use in a human architecture.

By 2021, Orion and SLS will be ready for missions in cis-lunar space and allow NASA and our partners to begin demonstrating capabilities and operations concepts for managing the risks of exploration missions further away from the relative safety of LEO. The Asteroid Redirect Mission (ARM) will use a robotic spacecraft with an advanced solar electric propulsion system to retrieve a small asteroid or a boulder from a larger asteroid and return it to a stable orbit in cis-lunar space. Human exploration of the asteroid will follow, with astronauts collecting select samples real time, demonstrating sample containment, and returning the samples with them in the Orion spacecraft. Astronauts will also assess the potential for this asteroid to provide resources in-situ.

NASA is collaboratively working with international partners to define a technically feasible and programmatically implementable global strategy for deep space exploration. This is important because sustainable journeys to Mars will only be possible with the contributions and capabilities of many nations working together. Asteroid Redirect Mission formulation work and related work has been shared with the international space agencies participating in the International Space Exploration Coordination Group (ISECG)[1]. Through these collaborative discussions, a common understanding of the value and opportunity provided by crew in cis-lunar space was established and reflected in the updated Global Exploration Roadmap.

PIONEERING SPACE: NASA'S EXPLORATION STRATEGY

Exploration and pioneering have inspired people and influenced human prosperity significantly over the last 2000 years. Nations that have explored, have benefitted significantly; both economically and culturally. Initial explorers bring back knowledge and opportunities which enable people who follow to best prepare to capitalize on subsequent journeys. It is this pioneering spirit – the journey into the unknown in search of benefits – which drives NASA's exploration planning. Some benefits can be anticipated, such as innovative new technologies, scientific knowledge and inspiration. History has shown that other benefits, just as important, cannot be imagined at the start. Discoveries can be expected which lead to tangible and intangible benefits to humanity (Ref 2). The pioneering spirit embodies our motivation to explore the solar system in a manner that is sustainable over time and leads to long-term human presence on the surface of Mars. NASA's exploration strategy is captured in the recent publication *Pioneering Space, NASA's Next Steps on the Path to Mars* (Ref 3) and summarized here.

Why are NASA and its international partners so interested in sending humans to Mars? Agency investments in human space exploration capabilities will continue to drive technologies and innovations which have application to other uses, both on Earth and in space. Sustainable missions to Mars will require technologies and capabilities we don't have today. Mars has a history, geology and climate—as well as accessibility—that make it an ideal location on which to study the most pressing questions of solar system origins, including those involving the search for life beyond Earth and comparative planetology. It also contains resources that could sustain human presence over the long term.

[1] In alphabetical order: ASI (Italy), CNES (France), CNSA (China), CSA (Canada), CSIRO (Australia), DLR (Germany), ESA (European Space Agency), ISRO (India), JAXA (Japan), KARI (Republic of Korea), NASA (United States of America), NSAU (Ukraine), Roscosmos (Russia), UKSA (United Kingdom)

The foundation for human exploration is the ISS. Space agencies are conducting many types of activities onboard the ISS that are essential for understanding and limiting the risks associated with long duration human missions beyond LEO. Having the ISS available until at least 2024 would ensure the highest priority research and other activities can be performed, as well as enable a solid rationale for commercial human activities in LEO, a necessary enabler of pioneering space (Ref 4). Exploration preparation activities include human research, technology demonstration and activities to demonstrate deep space exploration operations techniques. Perhaps most importantly, they involve improving reliability and performance (including lower mass and volume) of the critical systems supporting the ISS to meet the challenging requirements of deep space exploration missions.

The journey to Mars begins in cis-lunar space. Cis-lunar space (sometimes called the lunar vicinity) is an important locale for demonstrating in-space technologies and capabilities for deep space trajectories and orbits. It is a place to learn to manage the risks of operations in deep space while still close enough for early and contingency returns. Here, we can also use the presence of the crew to explore, discover and inspire. In this way, cis-lunar space is considered a proving ground for Mars. Missions to Mars will required advancements in radiation protection, propulsion, life support, space suits, and entry/landing techniques, just to name a few. In short, advances are needed to our current capabilities if we are to safely and sustainably explore and pioneer. Missions to the proving ground of cis-lunar space, like the Asteroid Redirect Mission, are a key initial step in the journey.

To pioneer space, including to the surface of Mars, we must progress from 'Earth dependent', in our terminology for defining and managing missions, to 'Earth independent'. An 'Earth independent' approach can be described by saying that crew must be able to remain safe and productive without most of the support provided today in LEO. There will not be a supply chain of logistics missions delivering fresh food, spares and other life support consumables, such as water. There will not be continuous real-time communication with the ground for planning and managing day to day activities. There is no possibility to quickly return an ill or injured crewmember for medical care. These challenges are in addition to well-known technical challenges mentioned above, such as radiation protection and advanced in-space propulsion. Approaches to addressing all of these challenges and risks must be developed and demonstrated before human missions to Mars can be conducted. The Asteroid Redirect Mission is an affordable opportunity to demonstrate many in-space capabilities needed and move towards an 'Earth independent' state of readiness (see Figure 1).

As shown in the Global Exploration Roadmap, extended duration missions in cis-lunar space are envisioned. These missions are enabled by delivery of an evolvable deep space habitat. The habitat could be designed for deep space exploration and based on ISS expertise and lessons learned. It would enable the presence of the crew to master deep space operations techniques and conduct research and technology demonstrations which need the deep space environment. The crew could use the unique cis-lunar vantage point to study the Earth, the Moon and deep space, perhaps even assisting in the return of lunar or Martian samples collected robotically. A crew-tended habitat spacecraft would enable demonstration of advanced systems in the deep space environment and drive the ability to keep them operational without continued crew presence and without the supply chain enjoyed by the ISS. In summary, missions in cis-lunar space, including the ARM, present a needed and affordable opportunity to prove the reliability of critical systems and operations techniques on which missions into deep space will depend.

In NASA's strategy, cis-lunar proving ground missions are followed by missions deeper into space, perhaps to the Mars system. NASA is studying new Mars mission architectures, building on Design Reference Architecture 5 (Ref 5) by applying a new set of driving principles and assumptions which are captured our space exploration strategy white paper, *Pioneering Space*. These include re-usable in-space infrastructure, evolvable capabilities which can be used for multiple destinations, and partnerships. This

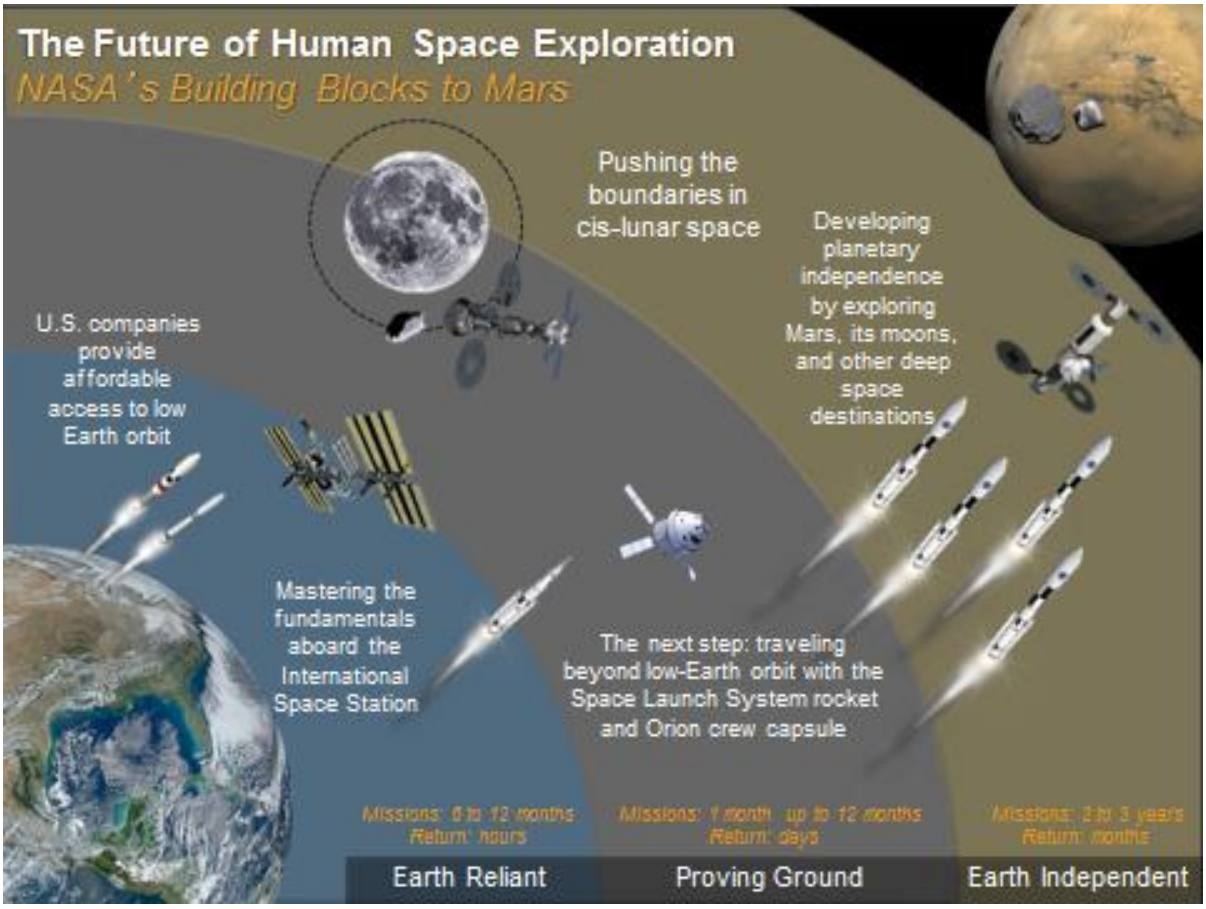

Figure 1: NASA's Building Blocks to Mars, the importance of cis-lunar space.

work is part of what is referred to as the Evolvable Mars Campaign (Ref 6). It is not the intent of the Evolvable Mars Campaign to identify a particular design reference architecture for sending humans to Mars. The intent is to evaluate a variety of architectures that reuse expected capabilities in order to guide near-term investments and understand elements of sustainability. One class of architectures is a split mission Mars approach which utilizes advanced solar electric propulsion (SEP) busses directly derived from the ARM SEP bus to preposition propulsion stages and habitats into Mars Orbit. NASA is studying several variants of combined chemical and SEP propulsion use and single and split habitat strategies to enable Mars vicinity and future Mars Landing missions (Ref 7).

THE ASTEROID REDIRECT MISSION

The ARM is an affordable, near-term, and compelling mission using several critical in-space exploration capabilities under development within NASA that enable many future missions on the journey to Mars. The ARM robotic mission will demonstrate high power, long life SEP for future deep space exploration, as discussed above. By redirecting a small asteroid from its native orbit or boulder from a larger asteroid to a stable lunar orbit, the robotic mission also sets up an exciting cis-lunar proving ground mission for the crew in the mid-2020's. The crewed mission of 27-28 days will use the Space Launch System (SLS) heavy-lift crew launch vehicle; Orion multi-purpose crew vehicle; advanced technologies and systems for rendezvous and extra vehicular activities (EVA); the International Docking System; and crewed/robotic vehicle integrated stack operations in deep space orbits.

Mission Description

The ARM robotic mission will capture and redirect a cohesive asteroid mass to a stable, crew-accessible lunar distant retrograde orbit (DRO) (Ref 8). One approach, Capture option A, for this robotic mission is to rendezvous with a small Near Earth Asteroid (NEA), with 4-10 meter mean diameter and mass up to ~1,000 metric tons, in its native orbit. The target asteroid will be 'captured' and redirected to a lunar DRO (see Figure 2). Capture option B is to rendezvous with a larger NEA (100+ meter diameter), collect a boulder typically 2-4 meters in size, and return the boulder to the same orbit (see Figure 3). Both options can also demonstrate basic techniques for slow push planetary defense operations.

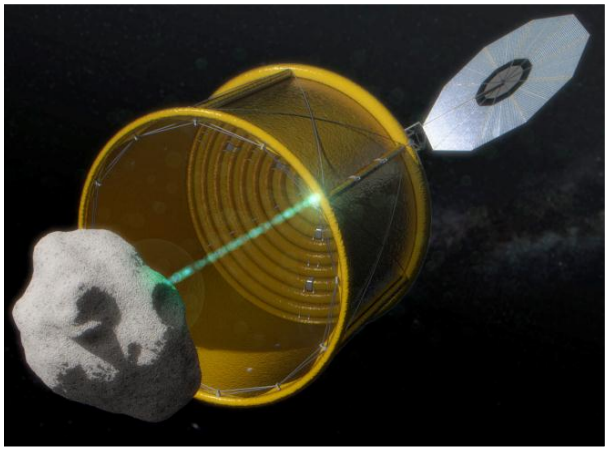

Figure 2: Capturing a small asteroid for return to the DRO.

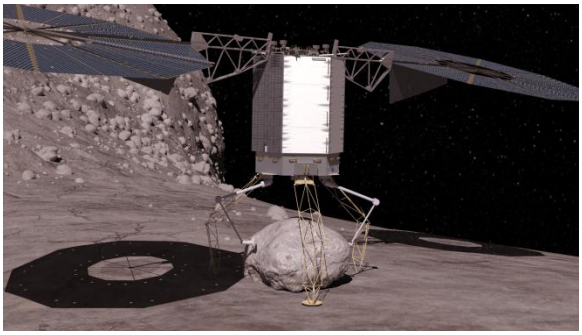

Figure 3: Removing a small boulder from a larger asteroid for return to the DRO.

Once the asteroid mass is returned to the proper orbit in cis-lunar space, the ARM crewed mission will be launched. The Orion spacecraft serves as the crewed transportation vehicle, habitat, and airlock for the reference mission concept. Orion will be launched into cis-lunar space on the SLS, allowing it to rendezvous and dock with the robotic spacecraft to demonstrate early human exploration capabilities including longer duration operations in deep space, rendezvous and proximity operations, life support and EVA capabilities. Two EVAs, each four hours in duration, are currently envisioned to explore, select, and obtain samples via a variety of sample collection options being examined.

The ARM is a significant step in human exploration beyond LEO. The systems proven on this mission will provide for a sustainable path to longer duration missions in deep space, developing the capabilities needed ultimately for missions to Mars. Several highlights are summarized below:

Pre-emplacement with SEP

The use of advanced SEP on ARM to maneuver the target asteroid through a trajectory similar to interplanetary transit will be the pathfinder demonstration in the use of advanced SEP for moving large objects in such applications.

Integrated crewed/robotic vehicle operations

The Asteroid Redirect Mission will provide an opportunity for integrated crewed/robotic vehicle stack operations in deep space. Human spaceflight has several examples of crewed/robotic vehicle interaction in LEO, such as the Space Shuttle Hubble Repair missions. Strengthening the collaboration between human and robotic vehicles is an important objective of the space agencies who have contributed to developing the GER because this human/robotic partnership promises to enable an expanded set of benefits to be delivered through space exploration investments (Ref 9). However, these interactions in deep space present new challenges. The automated rendezvous sensor suite required to perform docking must operate without the assistance of Global Positioning Satellites for navigation and must operate more quickly than Deep Space Network tracking can accommodate. The rendezvous sensor suite can provide a common suite that can be used to support multiple future exploration missions. Once docked, the crewed vehicle and robotic vehicle will have to operate as an integrated stack.

Advanced EVA Systems

Advanced EVA systems under development support multiple Global Exploration Roadmap scenarios. The Modified Ascent Crew Escape Suit (MACES) can serve as the Orion Launch and Entry Suit for all Orion flights. In the event of a contingency, the MACES suit would operate as an EVA suit an Orion umbilical. Improvements to the MACES design currently being tested increase EVA mobility in and allow the MACES to interface with a portable life support system. By incorporating these enhancements into the MACES design, the MACES suit and portable life support system could be used to conduct two 4-hour EVA's to collect asteroid samples. The improved MACES design can evolve to support future missions.

Sample Selection, Handling and Containment

Asteroid mission EVAs are designed to enable asteroid sample identification, collection, and containment. In the current ARM crewed mission concept, the crew translates directly from the Orion capsule to the robotic vehicle to prepare for sampling operations. Initially, they will conduct preliminary characterization and photo documentation. Then they will obtain the samples. All of these samples will be sealed in their own separate bags and then stowed in a larger container for return to Earth. Core tubes and other samples may be put in a separate stowage container and kept at ambient conditions (i.e., frozen temperatures, vacuum, etc.). ARM sampling and containment operations would be the first time that astronauts have collected and returned extraterrestrial samples to Earth since Apollo. The mission will help pave the way for future sample and collection activities for solar system samples (e.g., asteroids, Mars, the moons of Mars, etc.) where humans are in the loop

INTERNATIONAL COOPERATION

NASA's exploration strategy includes international cooperation. The partnerships we have developed through development and operation of the ISS demonstrate how capabilities from several agencies contribute to building an endeavor that is stronger than the sum of its parts. Under NASA leadership, capabilities and expertise provided by the US, Russia, Japan, Europe and Canada have realized a robust and capable laboratory. All ISS partners have demonstrated the expertise necessary to extend the capabilities developed for the space station to make critical contributions to the challenges which will face future exploration partnerships. For example, NASA and Roscosmos have developed transportation systems, life support systems, and many other critical capabilities. Europe and Japan have expertise in cargo transportation systems and some critical habitation capabilities. Canadian robotics systems were instrumental in assembly of the ISS and now are used for servicing the laboratory. These are just examples of capabilities which can be extended to support exploration mission critical needs.

The demonstrated interdependence on ISS catalyzed growing collaborative international strategic planning efforts in human space flight where common goals and objectives are established and national capabilities and long-term interests are considered. The ISECG has provided a forum in which stakeholder equities from all participants can be understood and considered to enable a strategy that is sustainable over the long term. Effective leadership will be essential to long term success. NASA engaged fully with ISS partners and other space agencies in discussions to lay the groundwork for future partnerships in space exploration through this collaborative work of twelve space agencies over the past four years. NASA played a lead role in development of the Global Exploration Roadmap, an international strategy for human space exploration, beginning with the ISS and the step-wise extension of human presence into the solar system, with human missions to the surface of Mars as the driving goal.

CONCLUSION

NASA's exploration planning effort reflects the importance of human space exploration in the U.S. by focusing on the foundational capabilities and technologies which will ensure government investments continue to drive innovation and enable exciting missions as part of a step-wise path to Mars. NASA is focusing on developing these initial capabilities while collaboratively working with international partners to define a technically feasible and programmatically implementable strategy for deep space exploration. With NASA's developments for beyond LEO exploration, we are demonstrating our desire to remain leaders in space exploration.

The Orion and SLS vehicles are foundational exploration capabilities which are evolvable as exploration objective demand. The ARM and other cis-lunar proving ground missions will demonstrate capabilities and operations concepts for managing the risks of exploration missions further away from the relative safety of LEO.

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