Accelerating Martian and Lunar Science through SpaceX Starship Missions

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Abstract

SpaceX is developing the Starship vehicle for both human and robotic flights to the surface of the Moon and Mars. This two-stage vehicle offers unprecedented payload capacity and the promise of lowering the cost of surface access due to its full reusability. An individual Starship spacecraft is being designed to fly large crews to another planetary surface, many of whom could conduct long-term science investigations taking advantage of the support infrastructure SpaceX intends to build. At present, the focus of SpaceX is on reaching Mars and providing relatively near-term opportunities for expanding humanity on the Red Planet. Our purpose here is to focus on the important research benefits that could arise from an effective partnership between NASA's Science Mission Directorate and SpaceX.

The Starship vehicle provides tremendous planetary research potential, but NASA currently lacks a mechanism for the planetary community to develop or fly payloads on Starships to either the Moon or Mars. While NASA's PRISM (Payloads and Research Investigations on the Surface of the Moon) and CLPS (Commercial Lunar Payload Services) programs are pathways for some lunar mission payloads to reach the Moon, NASA does not have a similar on-ramp for the planetary community to develop or fly payloads that could fully take advantage of Starship flights to the Moon and Mars. Starships can accommodate payloads that are notably different than traditional NASA payloads. Payloads can be much larger and heavier, eliminating the need for the costly reductions in size and mass required for traditional NASA payloads. Starships can fly multiple payloads and instruments on individual flights to reduce overall risk, and significantly more power can be available for the payload. Additionally, SpaceX's intended mission cadence opens up more frequent flight opportunities which has a number of advantages for enabling increased science and broadening community participation in planetary science activities. However, to capitalize on such opportunities, NASA must develop a funded program aligned with the development approach for Starship, including a rapid development schedule, relatively high risk tolerance compared to traditional planetary science missions, and ultimately a high ratio of potential science value for the dollars spent if successful. Such a program would enable the planetary community to participate in sending science and exploration payloads to these planetary destinations, which will advance science objectives outlined in the NASA Decadal Survey, NASA Strategic Plan, and similar guiding documents.

Starship capabilities

An appreciation of Starship's capabilities is important for understanding how and why this vehicle can provide unprecedented opportunities for the planetary science community to fly payloads to the Moon and Mars, thus advancing NASA planetary science and exploration. The overall Starship architecture is shown in Figure 1 (Musk 2018). Starship will be launched by a SpaceX Super Heavy Booster. This two-stage vehicle (Super Heavy first stage and Starship as the second stage) is fully reusable and can transport payloads to Earth orbit, the Moon, and Mars, along with being able to support a number of other missions including to Venus, asteroids, or elsewhere in the Solar System. Starship will also serve as the lander for lunar and Martian human and robotic missions, with payload volume and configuration adjusted for specific mission types. Starship missions will utilize in-space propellant transfer, enabled by Starship's substantial LEO performance capability and rapid launch cadence. The booster launches Starship into Earth orbit, where the Starship is refilled with CH_4 and O_2 by tanker flights from Earth (tankers are Starships which carry only propellant as payload), typically prepositioned in advance of the launch of primary payload. Both boosters and tankers return to the launch site for reuse. The refilled Starship vehicle then travels to the Moon or Mars and descends to the surface. Refilling Starship in orbit effectively resets the rocket equation, allowing for large payloads to be transported to these planetary destinations.

Starship is 9 m in diameter and 50 m in length. The vehicle is capable of delivering ~100 metric tons of payload to the lunar or Martian surface and has both forward and aft storage capacity (one configuration is a forward cargo section with a capacity of ~1100 m^3 and three aft cargo sections, each with capacities of ~50 m^3). Initial payloads will require significant autonomy for deployment and operations, while future payloads may employ crew oversight once a human presence has been established. Starship is also capable of returning crew and cargo from the Moon or Mars to Earth with 10s of tons of return mass depending on propellant refilling architecture details. Many early Starships are expected to remain on the planetary surface where they can be used for a variety of applications. To return large payloads to Earth, the vehicle is nominally refilled with propellants produced from local resources processed through a surface propellant production plant (i.e., ISRU, in situ resource utilization) for Mars missions, while lunar return missions can either make use of local resources or leverage propellants brought from Earth. Starship then launches from the lunar or Martian surface and returns directly to Earth.

Starship Robotic Flights

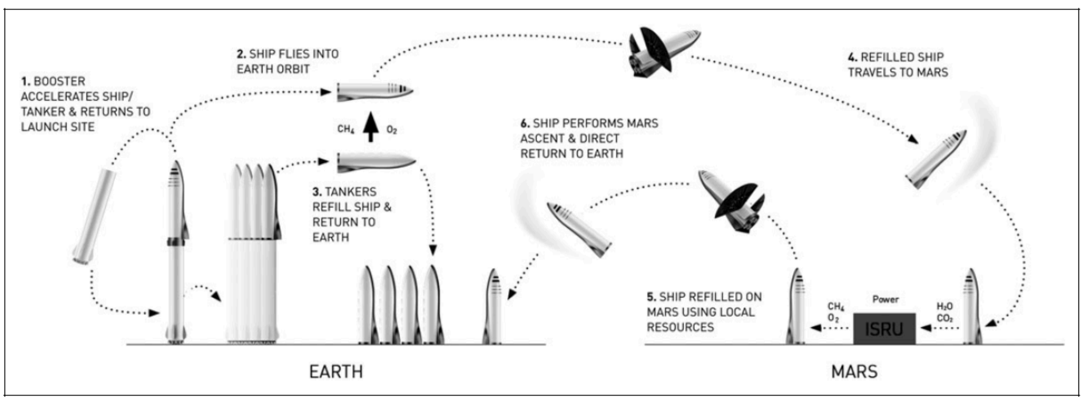

Figure 1. Mars transportation architecture (Musk 2018).

Starship has the capability to fly humans to the surface of the Moon and Mars. An ultimate objective of SpaceX is to develop self-sustaining cities on Mars, and current SpaceX architecture plans call for multiple Starship flights to be launched to Mars at every launch opportunity (~2 years). The first set of Starships launched to Mars will be uncrewed and are intended to demonstrate the capability to successfully launch from Earth and land on Mars with human-scale lander systems. These uncrewed vehicles will also provide the opportunity to deliver significant quantities of cargo to the surface in advance of human arrival. Local resource characterization, pre-placement of supplies, infrastructure development, and technology testing should be accomplished on these first Starship flights or subsequent uncrewed Starships, depending on the timing and availability of payloads for flight. In addition, such missions could enable delivery of mobile robotic assets that could be used to conduct planetary science research either autonomously or through high-latency teleoperation.

Starship can also fly to the surface of the Moon (Figure 2), along with deploying and retrieving very large payloads in cislunar space. Although not on the critical path for flights to Mars, flights to the Moon do provide the opportunity to test and demonstrate Starship systems closer to Earth prior to the longer journey to Mars. More frequent flights to the Moon than to Mars are feasible due to orbital dynamics, and thus significant capabilities can be developed and tested at the Moon prior to Mars missions. Robotic payloads deployed from Starship cargo flights to the Moon could greatly accelerate the pace of lunar scientific research.

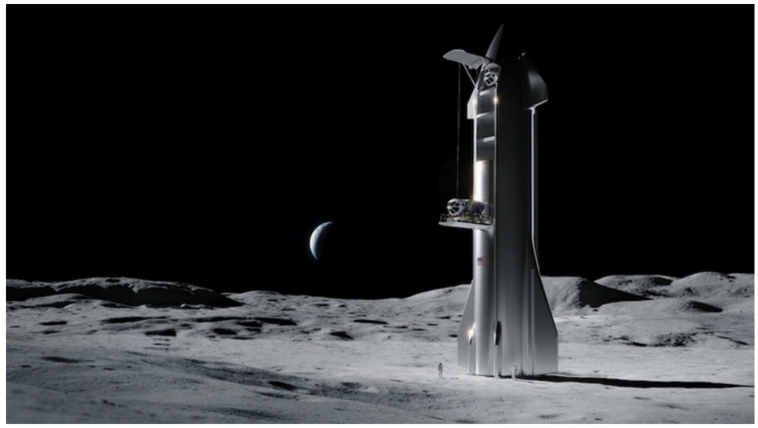

Figure 2. Artist rendering of SpaceX Starship on the lunar surface. Credit: SpaceX.

Starship Human Flights

Starship flights carrying humans to the Moon or Mars will follow the launch of uncrewed Starship vehicles to these destinations (Figure 3). In the case of Mars missions, the SpaceX plan anticipates there will be multiple cargo Starships on the surface which can support the arriving personnel flights. Crewed Starships will have on the order of 1100 m^3 forward space (most of which will be pressurized for human habitation), an 800 m^3 liquid oxygen (LOX) tank, and a 600 m^3 methane tank. Both tanks have a stainless-steel primary structure, and may be repurposed later as pressurized living space on the surface of the Moon or Mars. These first crewed Starships will likely each have about 10-20 total people onboard with an additional 100+ metric tons of available cargo mass per Starship. Cargo carried on these flights will include additional equipment required for human health and productivity during transit to the Moon or Mars and on the surface. Current SpaceX mission planning includes the intention that these vehicles will also carry hardware needed to support the human base including equipment for increased power production, water extraction, LOX/methane production, pre-prepared landing pads, radiation shielding, dust control equipment, exterior shelters for humans and equipment, etc. We suggest that the manifest could also include science payloads designed and built using NASA funding. Humans will likely live on the Starship for the first few years until additional habitats are constructed, so the radiation risk must be assessed and mitigated with equipment planned to support this initial infrastructure. The first wave of uncrewed Starship vehicles can also be relocated and/or repurposed as needed to support the humans on the surface. These vehicles will be valuable assets for storage, habitation, and as a source of refined metal structures and resources. They also could accommodate scientific research laboratories.

Figure 3. Artist rendering of a Mars base built with SpaceX Starship missions. Credit: SpaceX.

Planetary Science Enabled by Starship

Given the Starship's anticipated low cost, high payload capacity, and potential for high flight cadence, the opportunities presented for planetary science missions have the potential to dramatically increase our progress towards NASA Planetary Science & Astrobiology goals and objectives. Building upon the NASA CLPS paradigm (Bussey et al. 2019), use of SpaceX Starships will allow for increased flights for science experiments, technology demonstrations, and capability development to enable human spaceflight missions through NASA partnership and purchase of flight payload accommodation. High priority science objectives as outlined in the Decadal Survey and NASA Strategic Plan for the Moon and Mars can uniquely be achieved through flights to lunar/Martian orbit and/or to the surface of these planetary bodies. In addition, Starship has the ability to deploy orbiters on approach. This capability would provide the opportunity to deliver either relatively large orbital assets with sophisticated remote sensing instrumentation and/or many smaller satellites that could serve a variety of purposes, including development of communications or meteorology networks.

Starship is designed to lift off from its planetary destination and return to Earth, thereby allowing not only the return of crew members but also the return of unprecedented quantities of lunar and Martian samples to Earth for scientific analysis. Because Starship can return tens of tons of payload from the surface of the Moon, the return sample mass of lunar samples from a single mission would dwarf the combined total returned mass of all lunar samples from all sample return missions to date. Many samples with greater sample variety will allow for more scientifically robust analytical studies in laboratories on Earth. Removing the need to severely high-grade and down-select samples on the Moon and Mars will also enable opportunistic science from returned samples to degrees previously not achievable. Never before has the science or exploration community had the potential to send such payload capacity to these destinations and return as much sample material as can be accommodated by Starship. The scientific progress achieved would be unprecedented.

Human Exploration Enabled by Starship

Human exploration of the Moon and Mars is also enabled by the Starship vehicle. NASA has ambitions for sustainable human exploration of the Moon and forward to Mars. A first start towards these goals, particularly focused on the Moon, is the selection of three companies to participate in the Artemis human landing systems (HLS) program. SpaceX has been selected for development of Starship under the HLS program. A unique aspect of Starship is its capacity for large-scale transport of people to a planetary surface. This could drive accelerated development of a sustained presence on the lunar surface. The same approach could apply to Mars. The planetary science community must be prepared to take advantage of these flight mission opportunities, including on the many uncrewed landings anticipated as part of the SpaceX plan.

Science and Human Exploration Synergy

The ability to deliver large payloads and significant numbers of crew to the surfaces of the Moon and Mars highlights the need for an integrated strategy among NASA's Science Mission Directorate (SMD), Human Exploration & Operations Mission Directorate (HEOMD), and Space Technology Mission Directorate (STMD). Successful program execution for cutting-edge technology to enable SMD science and sustained human exploration will be predicated on close partnership amongst these entities, working under the driving mantra that "science enables exploration and exploration enables science". Such close partnerships are uniquely enabled by Starship because game-changing progress will be made on each of these fronts. The capability of placing large payloads on the Moon and Mars will also allow for greater international collaboration, where international partners could provide unique technologies and instruments. This model is consistent with the ISS (International Space Station) program, which NASA spearheaded.

A prime example of a mutually beneficial project amongst SMD, HEOMD, and STMD is ISRU of water ice on the Moon (and Mars). We consider the lunar case here, but the logic applies to Mars as well. A first step in lunar ISRU is to understand the form, distribution, and character of the subsurface ice near the lunar poles of the Moon (Sanders 2015), both in permanently shadowed regions (PSRs) and in regions that receive some sunlight each month but still retain low subsurface temperatures capable of retaining volatiles at shallow depths (Colaprete et al. 2019). This phase of resource exploration and prospecting will not only provide critical information to inform ISRU accessibility, extraction, and processing techniques, but will also answer fundamental scientific questions regarding lunar polar volatiles. Specifically, the measurements to characterize ice for ISRU are also relevant for addressing scientific questions such as understanding the origins of the Earth-Moon system through measurement of primordial lunar volatiles, understanding the inventory of volatile delivery in the inner Solar System over geologic time, understanding the lunar hydrologic cycle and the role of volatile migration over various timescales, and the understanding of prebiotic and abiotic chemistry in the space environment of airless bodies. This scientific information is fundamentally important for lunar science and science on airless bodies.

In addition to the scientific return, understanding the emplacement mechanisms of water ice and other volatiles is critical for developing predictive capabilities to map expected areas of ice concentrations to refine ISRU site selection for mining and processing. The concentration, state, and form of the volatiles are necessary information to inform requirements for ISRU extraction and processing hardware. New technologies will require development and testing to enable ISRU activities on the lunar surface in the polar regions, informed by what is learned during these ice prospecting missions.

Programmatics for capitalizing on Starship flights

The capabilities of the Starship vehicle to transport unprecedented quantities of cargo and crew to the lunar and Martian surface will require a new support structure within NASA to enable the NASA planetary science community to participate and provide payloads for these flights. SpaceX envisions an accelerated schedule for flights, but NASA's traditional schedule for selecting and flying planetary payloads is not necessarily consistent with this timeline. For example, SpaceX is aggressively developing Starship for initial orbital flights, after which they intend to fly uncrewed flights to the Moon and conduct initial test flights to Mars at the earliest Mars mission opportunity, potentially as soon as 2022, or failing that in the 2024 window. Since the launch window is significantly less restricted for the Moon, it is likely that the first Starship landings will be on the lunar surface. (Even in the case of a first Starship *launch* to Mars, during its six-month trip to the Red Planet it would be feasible to send a Starship to land on the lunar surface prior to the Mars landing). In order to take advantage of these opportunities, a new funding program within NASA is needed to provide the opportunity for members of the community (within and outside of NASA) to fly robotic payloads on these flights. A program based on NASA's PRISM, run in conjunction with CLPS, or an SMD SALMON (Stand Alone Missions of Opportunity) call, could be a viable pathway to create a robust portfolio of payloads that could be ready for flight in a short timeframe to achieve SMD, HEOMD, and/or STMD objectives. In order to be successful given the flight schedule for SpaceX missions, this funding program must be nimble enough to select proposals for funding and make grants within just a few months after proposal submission.

An additional benefit of the increased cadence and capacity for robotic and crewed flights to the Moon and Mars offered by Starship will be the ability to extend the opportunity for flight mission participation to a broader cross-section of the planetary science, human exploration, and technology communities. Over the past 15 years, women have been ~25% of the planetary science community but comprised only ~15% of planetary mission science teams (compared with 51% of the general population). Black and Hispanic people make up 13% and 16% of the U.S., respectively, but comprise just 1% of the nation's planetary scientists (Voosen 2017). NASA has made great strides in recent years to promote increased diversity within the planetary science community (as an example, the expectation of a "diverse and inclusive" team for the latest round of New Frontiers mission proposals), in addition to numerous additional initiatives. The increased cadence of Starship flights, lower cost per instrument deployment, and less need for extreme engineering optimization will provide even more opportunities for NASA to continue its commitment to enable more people and a broader segment of the community to contribute to spaceflight missions, as well as provide exceptional opportunities for public engagement of these planetary spaceflight missions.

Conclusions

The SpaceX Starship system fundamentally changes the paradigm for NASA science, technology development and testing, and human exploration of space. Starships flown to the Moon and Mars will provide opportunities to deliver massive cargos and large numbers of people to enable sustained and self-reliant human off-world presence. In addition, the return of many tons of samples from the Moon and Mars to Earth for scientific analysis will be enabled. The types of payloads that might be used to achieve SMD, HEOMD, and STMD objectives could be much different than those designed for traditional NASA flight opportunities with their stringent mass and volume constraints. In addition, broader segments of the community (including international partners) will have the opportunity to participate in spaceflight opportunities (both human and robotic) since more flights with more payload will be flying to the Moon and Mars than ever before. NASA could actively expand the roster of flight mission PIs and team members to include more early career professionals as well as marginalized and underrepresented groups.

In order to take advantage of the impending Starship flights to the surface of the Moon and Mars, NASA will need to develop a new funding program consistent with the mission timelines for rapid flights planned by SpaceX. To be most effective, planning should begin immediately to prepare for payloads on the first uncrewed Starship flights, likely first to the Moon and then for Mars. Starship missions to the lunar surface can be an important stepping stone for reaching Mars both technically and programmatically. The Moon can be a testbed and demonstration platform for ISRU technologies as well as Starship operations.

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