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Phobos, Possible Refueling Station for a Single Stage to Orbit Vehicle

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Abstract

Numerous architectures have been proposed for a human mission to Mars. Most of them are appropriate for the first missions but in the long term, important improvements are expected to reduce the complexity and costs of the missions. Assuming the presence of water and carbonates on Phobos, which is suggested by several experts, it might be possible to use this Moon of Mars as a refueling station for rockets coming from Earth and Mars. In the long term, an interesting perspective is to manufacture on Mars a single stage to orbit space plane, called Albatros, that could be used to transfer crews and cargo from Mars orbit to Mars surface and the other way round. Technical specifications and illustrations of this SSTO are given as well as a range of possible applications. This idea was developed in a proposal in response to the recent Mars Society City State Design Competition, where we achieved the third place, with “Foundation”.

Keywords: Mars settlement, Phobos, SSTO.

1. Introduction

The internal composition of Phobos is uncertain. In several papers, it is suggested that Phobos is an old moon of Mars and has plenty of interesting resources like water and carbonates, which could be exploited to produce propellant [1-4]. If it is confirmed, Phobos could play the role of a refueling station for vehicles coming from the Earth or from the Martian surface. For the first human missions, the construction of a space station on Phobos would certainly be inappropriate, but in the long term, assuming a constant human presence on the red planet and an interest in optimizing transportation means and reducing costs, the idea deserves to be developed. It is proposed in this paper to investigate the idea and to determine what could be the role of Phobos exactly. Section 2 is a review of Phobos' physical features. Section 3 presents the concept of a space station on Phobos. It would be used as a refueling station for vehicles coming from Earth. Passengers and cargo would be transferred into reusable space vehicles that would land on the surface. Section 4 shows the design of the reusable space vehicle proposed. It is a single stage to orbit rocket called Albatross. In the long term, as such a vehicle should be built and assembled on Mars. The feasibility, industrial requirements and maintenance issues are discussed.

This paper is based on a concept that was originally developed for “Foundation”, a submittal to the 2020 Mars City State Design Competition organized by the Mars Society [6].

2. Phobos and Deimos

2.1 Chemical composition

Phobos and Deimos are the two moons of Mars. Despite numerous spectral observations, the composition of the moons is unclear [1,2]. In 1990, Fanale suggested that there is possibly water under the surface of Phobos [3]. According to the most recent studies, the composition is tightly linked to the origin of the moons [4,5]. There are two hypotheses: The first is the capture of an asteroid and the second is the accretion of debris after a giant impact on the surface of Mars that occurred billions of years ago. As their orbits are close to a circle and are contained in the equatorial plane of the planet, the second hypothesis is currently favoured. In this case the composition of the moons would be a mixture of material that originated from the impacting asteroid and the surface of Mars. Depending on the nature of the asteroid (carbonaceous or not), the ratios of the different chemical elements present would differ. However, as some elements come from the Martian surface, numerous light chemical elements would be present (e.g., carbonates and water) in non-negligible amounts. An important question, however, is to know why no trace of water is currently observed on the surface. According to Rosenblatt et al, volatile elements present on the surface of the moons may have been lost [4]. For that reason, carbonates and ice might not be present directly on the surface but might be found underground, as suggested by Canale [3].

2.2 Physical parameters

Deimos is orbiting very far from Mars, about 23 thousand kilometers, while Phobos is orbiting much closer at about 9.3 thousand kilometers. As the objective is to study the feasibility of a stopover space station for human missions to Mars, it is preferable to minimize the time and energy for the descent to the surface of Mars, as well as the time and energy for the ascent to the moon. Phobos is therefore the best candidate for a space station.

Table 1. Phobos and Deimos orbital parameters.

	Deimos	Phobos
Periapsis	23, 546	9, 234 km
Apoapsis	23, 471	9, 518 km
Orb. period	1.26 days	7 h 39 min
Radius	6.2 km	11.3 km
Surf. gravity	0.003 m/s ²	0.0057 m/s ²

3. Phobos as a refueling station and hub

3.1 Stopover before landing on Mars

In most human missions to Mars architectures, for example in NASA Design Reference Architecture or Salotti's version of Mars Semi-Direct, the mass of the landing vehicle is in first order approximation half the mass of the vehicle arriving in the vicinity of Mars [7,8]. The surplus is the mass of all systems required for entry, descent and landing:

- Heat shields.
- Thermal control system.
- Propulsion system for the last phase of the descent, engines, tanks and propellant.
- Landing legs.

If it is not required to land on the surface of Mars but to go to Mars orbit and land on Phobos, some mass savings are expected. The Delta V budget to go to Phobos is presented Table 2 [11,12]. There are two cases:

- Without aerobraking, the Delta V depends on several parameters, such as the planetary configuration, which could imply a plane change and the type of transfer (Hohmann or faster). It is about 2 km/s if no effort is made to speed up the interplanetary trip. Assuming an Isp of 350s (methane oxygen), the mass of propellant would be around 44% of the total

mass (Tsiolkovsky equation) and the mass of the wet propulsion system would be around 50%. It could eventually be much higher if a fast Earth Mars transit is implemented. This option is therefore not interesting in comparison with a direct to Mars surface option.

- With aerobraking, the propulsive Delta V is rather limited, on the order of 1 km/s, even if a fast Earth Mars transit is implemented. It could even be lowered if the aerocapture maneuver is stronger and the first apoapsis close to the altitude of Phobos. However, an aerocapture maneuver can also be used for a direct to Mars option. The descent is demanding in terms of heat shields and thermal control, but they are already needed for aerocapture and the resulting Delta V to reach the surface would be more or less the same, on the order of 1 km/s.

A small gain might still exist, but a stopover at Phobos for refueling or for the transfer onto another vehicle before going to the surface is therefore not very interesting.

Table 2. DeltaV budget from Mars transfer to Phobos.

	To Phobos, with aerocapture	To Phobos w/o aerocapture, on average
Mars transfer	962 m/s	2017 m/s

3.2 Refueling on Phobos for the return

Another important issue is the return to Earth. If a vehicle does not stopover at a space station in Mars orbit, it must bring all the propellant required for the return, which in turn would have an important impact on the mass of the propellant and systems for Mars orbit insertion. In the NASA reference mission, the impact depends on the specific impulse of the propulsion system [Nasa]. In general, from the chosen orbit, there is 1.5 km/s for trans-Earth injection. For chemical engines, the mass of propellant represents about 30% of the total mass of the return vehicle. There is however an additional impact if there is a propulsive Mars orbit insertion. In Salotti Mars semi-direct architecture, in which aerocapture is used for all vehicles, the mass of propellant for the return also represents about 30% of the total mass of that vehicle and there would be some mass penalty for scaling up the aerocapture systems. If some propellant can be manufactured on a moon of

Mars, it would therefore allow an important mass saving.

3.3 Refueling on Phobos for the next flight from Earth

In addition to that, other mission architectures deserve to be examined. Let us consider the architecture proposed by Space X with an interplanetary reusable vehicle called Starship. Though still in early development, according to Musk, 5 heavy launches would be required to refuel the Starship vehicle in LEO before each new mission to Mars. Using Phobos as a refueling station, it could indeed be possible to avoid two or three heavy launches to LEO by refueling on Phobos during the previous Mars-Earth flight. The tanks would be at least half full after trans-Earth injection, and this would allow huge mass savings for the preparation of the next flight. If two or three heavy launches were eliminated, the cost could probably be cut by a factor of two. Starships could still go to Mars first, but on the way back, they would stop over at Phobos for refueling. Another idea is to use other vehicles for the transitions between Phobos and Mars surface and the other way round. If there is a station on Phobos, there would certainly be a need to go to the station at any time for maintenance or for swapping working teams. The idea of a Single Stage To Orbit (SSTO) rocket is therefore interesting and further developed in the next sections.

3.4 Phobos as a spaceport hub

In the future, numerous martian bases will be built on the surface and some of them might be very distant from each other. In order to reduce the travelling time to each destination, Phobos could be used as a hub, in which new visitors or settlers could make a rocket change for a direct descent to a very close spaceport.

3.5 Interesting economic perspectives

Refueling on Phobos allows other interesting and competitive options for many destinations. Considering the long term perspective of a large settlement on Mars, the most important could be the design and production of satellites on Mars to be sent to high Earth orbits (e.g., geostationary). The transfer from Mars could be made in two steps: First sending the satellite to Phobos station using a SSTO (see next sections), then refueling and sending the satellite to Earth orbit. In terms of Delta V, it is indeed easier to send satellites from Mars to GTO than from Earth, with 8,7 km/s vs 13.1 km/s. See Table 3. And thanks to the refueling station, the maximum Delta V before refueling is on the order of 6 km/s. For such a low requirement, a reusable SSTO (Mars to GTO through Phobos and back) could be exploited and could help in reducing the total cost of the missions. This is

obviously for the long term, as the production of satellites requires important industries on the surface of Mars.

Other missions could also be interesting with a stopover at Phobos: missions to asteroids, missions to the Moon, robotic and human missions to other destinations in the solar system, like the moons of Jupiter or even further. In addition, if there are several permanent bases on the surface of Mars, a stop at Phobos station could be interesting to take a space taxi to the exact destination on the surface.

Table 3. Delta V budget from Mars to geostationary orbit through Phobos.

Mars to Phobos	Phobos to Earth transfer (GTO)	Earth transfer (GTO) to GEO	Total
5.5 km/s	1.9 km/s	1.3 km/s	8.7 km/s
Earth to LEO	LEO to GEO		Total
9.3 km/s	3.8 km/s		13.1 km/s

3.6 Propellant production

Let us assume, as suggested by Canale, that Phobos contains carbonates and water a few meters below the surface. There are different ways to produce propellant using these resources. As proposed by several authors for a Mars ascent vehicle, it is possible to produce hydrogen, methane, or ethanol, and to combine them with oxygen to get some thrust for a rocket [9,10]. Among the different options, the easiest is probably a rocket engine powered by cryogenic liquid methane and liquid oxygen.

- Oxygen can be obtained from water electrolysis and some energy. If large amounts of ice can be found, there is no difficulty to get that element, together with hydrogen.
- Methane can be obtained in several steps. First, the idea is to extract carbonates from the Phobos underground. Second, carbon dioxide can be produced by heating. Third, a Sabatier reactor can be used to transform carbon dioxide and hydrogen into methane.

In order to implement these reactions, a chemical unit is required together with a power plant and several other systems such as compressors, collectors and heaters.

4. Albatross, a SSTO rocket

4.1 Capacities and design

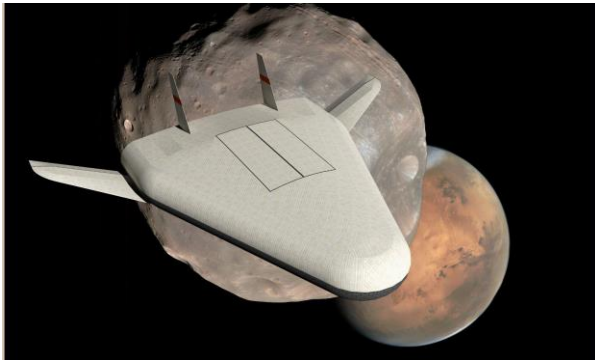


Fig.1. An Albatross SSTO moving in front of Phobos

On Earth, there have been many designs for a SSTO rocket and a single attempt to build one, the NASA X33 spaceplane. A precursor for the larger Venture Star design, it had a vertical launch and a horizontal landing. Its failure was linked to the construction of its fuel tank, and not an inherent impossibility of the design. As the atmosphere of Mars is not dense, horizontal landing could be difficult (very high speed) and the wings might not be justified. As the parameters for the entry and descent to the surface would be constrained by the orbit of Phobos, increased range using aerodynamic surfaces could nevertheless be interesting, to increase the accessibility on the Martian surface. The Albatross concept is inspired from the X33 prototype, itself a precursor for the never built Venture Star. Thanks to a much lower Delta V requirements, less than 6 km/s for the ascent to Phobos, the technical design is simpler. The lifting body form facilitates the entry and descent stage, with lower temperatures at entry, a lower deceleration peak, and the possibility of landing at higher altitudes on the surface. This vehicle can also be considered as a more specifically adapted version of Starship, the vehicle SpaceX proposes for missions to Mars.

Albatross characteristics:

- Size: Length: 21 meters; width: 25 meters
- Main propulsion system: LCH₄ and LO₂, specific impulse 319s.
- Total propellant: 240 tonnes.
- Dry mass: 30 tonnes (including shielding for descent)
- Maximum payload: 20 tonnes
- DeltaV: 5500 m/s

- Payload dimensions: Length: 7.5m; width:4.2m; depth 4m

4.2 Maintenance issues

The SSTO and any vehicle coming from Earth is likely to be unpiloted. Maintenance of the SSTO would therefore take place on Mars. As the martian landing and aerodynamic heating are likely to be the most difficult elements of the flight, this is a logical solution. Importantly, as the proposed SSTO would be relatively small and light (compared to Musk's Starship), it would be technically easy to transport it from the landing site to the maintenance site, and also to access to the highest parts of the vehicle for inspection.

The SSTO should have the capacity of bringing up maintenance personnel for the station if needed. The development of an unpiloted craft should also be easier and eliminate any risk to life. Automated orbital fuel transfer is also an essential part of many Mars exploration plans and should be old and reliable technology by the time a Phobos base is developed.

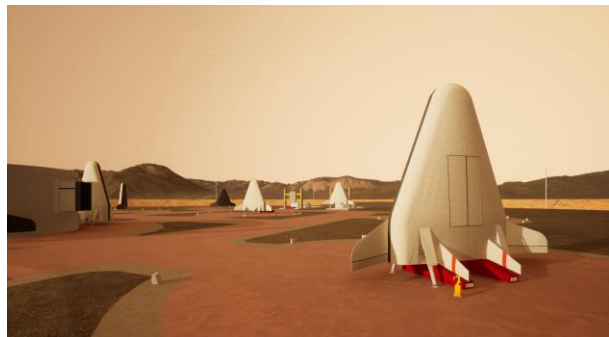
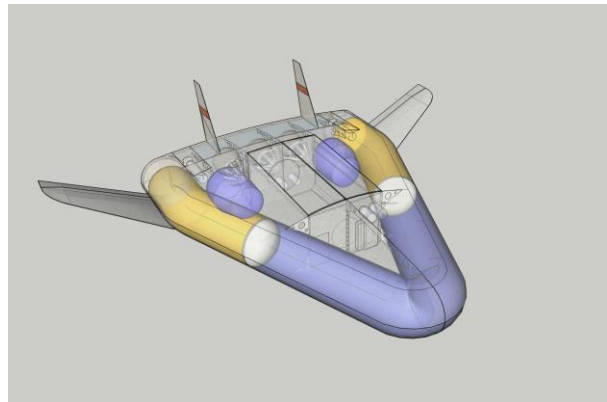


Fig.2. Albatross model and Martian landing area

4.3 Industrial requirements for the construction on Mars

Industrial production on Mars using In-situ resources for common materials should be favorable economically when compared to transportation costs from Earth.

The Albatross SSTO requires 30 tonnes of fabrication materials, mostly structural elements, tanks and heat shields. Aluminum is readily available on Mars and could serve as the main structural and tank material for the Albatross. Iron, silica and carbonates are also available in the Martian lithosphere (for instance in hematite, sand, and sedimentary terrain), and specific separation methods could be developed. There will be a local market on Mars for structural materials used in habitats that can also serve for the Albatross. In fact, the construction of a number of Albatross type vehicles would be a small demand compared to infrastructure requirements for a Martian settlement. Martian habitats need to be built from pressure resistant materials due to the very low martian atmospheric pressure; the same industry might serve the launch vehicle market.

Large scale in-situ production of methane and oxygen propellants is required for most Mars missions planned today and the infrastructure for this would serve for the Albatross as well. Using methane rather than hydrogen also reduces the size of the tanks significantly, leaving more space for payloads and reducing structural requirements. The lower deltaV requirements simplifies the construction of the spacecraft on Mars when compared to Earth, as the volume of the tanks is not such a large fraction of the vehicle. A vehicle the size of the X-33 may then be able to carry a payload practically the size of the one planned for the larger Venture Star.

A petrochemical industry is possible on Mars, using methane from CO₂ and precursor materials produced in the life support systems of a martian settlement. Products such as PVC, EPDM and other plastics can be produced using known methods and solar or nuclear energy.

Avionics and microprocessors might come from Earth in the early stages of production, until a local industry develops.

Relativity Space has proposed in its mission statement the use of 3D printing to produce a rocket on Mars using the technology it is developing for launchers on Earth [13].

5. Conclusion

The Japanese Martian Moon eXploration mission (MMX)[14], or the European candidate mission Phootprint [15], planned for 2024, are sample return missions that should provide answers to the origin of the Martian moons. It should also determine if water and carbonates are present in significant quantities. If sufficient resources are identified, then Phobos might serve as an important propellant source for the development of transportation infrastructures between the Earth and Mars and between Mars and the asteroid belt. A locally produced SSTO could serve as an efficient space plane to travel between the surface and the Phobos spaceport hub. It could also be used to move resources from Mars to orbit, and could reach Earth GEO at a significantly lower deltaV cost than from the Earth's surface.

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