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PHOBOS ON THE CHEAP

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Prior manned Mars exploration architectures have proposed, with good reason, that manned exploration proceed directly to the surface of Mars once we begin sending humans to the Mars system. Phobos on the Cheap proposes instead that we take a slow approach, incrementally building up towards an eventual manned landing. First, the propulsion area is addressed by providing a reusable low thrust deep-space propulsive ion drive tug disguised as a commercial transfer stage product for LEO to GEO missions. Once that vehicle has been flown and demonstrated, it begins being used for unmanned Mars missions, as it reduces the cost of delivering payloads to Mars substantially. When the tug has been proven in deep space applications, we expand the program to create a manned base on Phobos, suitable for long term habitation and teleoperation of Mars surface rovers, giving many of the benefits of humans on the surface with few of the costs. Finally, after the Phobos base operation has been built up and extensive robotic and teleoperated surveys have been completed, we develop a surface landing program sending humans to explore the most interesting sites identified in the teleoperated science program. Each of the steps independently is a low risk, low cost step, but together they march towards an ongoing, sustainable, and affordable manned Mars exploration campaign.

2.0 INTRODUCTION

The objective of Phobos on the Cheap is to conceal as much of the funding for an eventual manned Mars mission in other programs and objectives as possible, accidentally leaving us with a usable and affordable manned Mars program that has largely avoided exposure to the political process.

To attain that goal, we begin by proposing a mission architecture that looks like several other things, if presented in the proper light. We make those other things attractive, in commercial and scientific terms, and slowly progress onwards until an ongoing manned exploration program has just sort of happened, at reasonable cost and low dedicated investment.

3.0 ORBITAL DYNAMICS

Mission trajectory development done by Frank Crary and the author shows that optimal delta-V for solar-electric low thrust missions from Earth's vicinity (past escape velocity) to Mars with DS-1-like vehicle characteristics is 3.4-3.8 km/s for missions employing aerobraking at Mars, depending on model assumptions.

If we assume a staging station or staging orbit at geosynchronous orbit, total mission delta-V from staging orbit to Mars is 6.6 to 7.0 km/s. We will use 7.0 km/s for the following mission design and assume one-way trip times of 12 months, under continuous thrust.

Conveniently, this gives us roughly equivalent delta-V for the one-way trip from GEO to Mars, and for the round trip from LEO to GEO and back for a low-thrust tug.

4.0 THE TUG

The key to Mars missions is generally propulsion. Let us start then by examining our propulsion choice.

We need a tug that can do at least 3 things:

- Transfer large comsats from LEO to GEO in an effective commercial operation
- Ferry payloads for our manned mission to Mars to GEO staging
- Ferry payloads from GEO staging to Mars.

We chose a 20 ton overall vehicle size. This corresponds to one tug plus tug payload per Proton or EELV-H launch, the maximum sized launch vehicle likely to be available on an ongoing commercial procurement basis. This is broken down into a 10.5 ton tug and 9.5 ton payload. This size has a number of advantages, among them that if necessary it can be launched with separate tug and payload on 10 ton to LEO launchers. A 20 ton tug with a 20 ton payload would have other advantages, such as the ability to use off the shelf Mir type modules for the eventual crew hab, but shackles operations to the largest launch vehicles likely to be available and will always require on orbit mating of tug and payload. We choose a 10 ton tug and payload.

The tug has 6 tons of stored xenon propellant, enough for a delta-V of 8.0 km/s for the combined stack. The remainder of the tug is solar arrays, tankage, the xenon ion thrusters, power conditioning equipment, electronics, and structure.

To replicate the DS-1 performance parameters, giving acceptably short mission flight times, 49 DS-1 or XIPS type thrusters are used. Each has nominal thrust of 92 mN each at 2.3 kW input power. Total propulsive electrical power requirement is 112 kW at launch, providing 4.5 N of total thrust, or an acceleration of 2.25E-4 m/s.

The xenon is stored cryogenically, with passive insulation assumed. Liquid xenon has a density of 3.5 at -109C, well within passive cooling limits. This high density leads to efficient storage tanks.

The arrays drive the 125 kW power requirement at 1AU, giving us a 450 m^2 array area using 20% BOL efficiency. Arrays with specific power of 66 W/kg are assumed. No significant power storage is needed.

Structural requirements are minor, largely related to supporting launch loads. Self-contained guidance and control are provided, multiply redundant star trackers, redundant laser ring gyros for attitude stabilization, and modern solid state rad hard computers.

While relatively large, there is nothing unique or complex about the vehicle, and R&D costs should not exceed $1 billion in the worst case. Commercial development cost models indicate development might cost as little as $500 million. Specifically, no systems or technologies that are not currently off the shelf are proposed, simplifying the development to mere design and integration. The vehicle can be sold commercially for LEO ®GEO ferry purposes and will probably pay for itself in that role. If not, it should be possible to sell its R&D costs to NASA for use as a generic large exploration vehicle stage and bus. The commercial application would be preferred, as it could generate multiple vehicle sales and rapidly provide flight experience with the design. The vehicle should cost no more than $45 million per unit in volume production. Launch on a Proton or EELV-Heavy launch vehicle should run from $50 to $100 million more, providing lift for a tug and a payload. Two such launches would be required per mission to Mars, as the GEO to Mars tug must be hauled up to GEO as a payload in initial missions (later, refueling at GEO and continuing on with the same tug should be an option). Total transportation cost per 9.5 ton payload launched to Mars is therefore in the range of $300 million in the early phases of the program. In later phases, with reuse of the LEO -> GEO tugs and refueling in GEO, total transportation cost per 9.5 ton payload should drop below $150 million.

In the commercial market, the tug has considerable value transporting payloads to GEO. Assuming Proton launches, the payload to GEO would more than double (4.5 to 9.5 tons), with the cost for the launch vehicle plus tug going from roughly $80M to $120M, a reduction in price per ton of $17.7M to $12.6M. The cost decrease will be even more noticeable with more expensive launch vehicles, as the relative cost of the tug decreases.

This cost improvement must be traded off against increased time to market of the vehicles. Let us assume a 30% lower launch cost for the payload delivered to GEO, and a transfer time of 8 months (pessimistic). If the launch is initially 50% of the payload's total delivery cost, then the cost savings will be 15% total. This corresponds to an annual rate of return on the solar ion tug of 22.5%, which is well within commercial return ranges and much below the cost of capital (7-10%) over that time period. A complete business case including risk analysis is needed, but the high level examination appears that the vehicle clearly has commercial potential.

5.0 UNMANNED EXPLORATION

Now that we have propulsion squared away, conveniently paid for by someone else and self supporting, the next step is to begin large-scale exploration of Mars.

The first mission is to be a relatively quick and dirty flight using few new technologies. If we assume $250 million annual funding for Mars missions, then roughly $200 million will be available beyond transportation costs to deliver a 9.5 ton payload to Mars with 2 years funding.

Optimistically, this would purchase 10 Mars Pathfinder + Sojourner clones and 2 Mars Global Surveyor clones. Equipping the landers with long life nickel-hydrogen batteries will not increase cost much and should increase lifespan to years for both the landers and rovers. Pathfinder and Sojourner returned 15,000 pictures and several tens of million datapoints; with 10 times the lifetime with long life batteries, overall return for the whole ground mission (10 landers) would be over a million pictures. Using the public response from Mars Pathfinder and MGS as examples, and Leonard David's assumption that one picture is worth a thousand votes, this should generate enough interest to decide the next American presidential election in favor of future President-Elect Zubrin, therefore eliminating funding problems for future manned missions.

6.0 MANNED EXPLORATION

First Mission

After 3-4 launch opportunities worth of unmanned missions (6-8 years) the next phase is gently introduced. Phase I of the manned program does not jump to surface landings immediately. Instead, we send a manned base to the surface of Phobos, the inner moon of Mars, where the base modules are buried slightly in natural or explosively excavated holes for radiation shielding and the first crews are tasked to remotely operate rovers on the Martian surface.

This approach minimizes the risks involved in the manned mission profile and allows maximum telepresence science. It does not introduce any human presence, landing, ISRU, or other technologies, just zero-G systems and life support systems that should be mission qualified from Space Station (ISS or Mir) experience. The key here is to avoid R&D expenditures as much as possible. If we assume 6-year missions and about 50 m^3 per crewmember ("military" grade habitation volume corresponding to similar comfort levels to Apollo or nuclear submarines), two crew can fit in a short space station module sized hab facility (or a 25-foot Spacelab type module, or TransHab, or any similar option). With 3-ton structural masses, modules in this size range would have roughly 6-ton "payloads" for systems. About 1 ton is required for a reverse osmosis closed water cycle, 3 tons for biological ECLSS air recycling, and 2 tons remain for science payload, electrical systems, and the crew. This module design, single tug and single 10 ton module is known as the Option A architecture.

Alternatively, with minor redesigns the ion drive units can be used in pairs with Mir core module type 20 ton habitation modules, dropping the R&D for the modules to effectively zero and using designs with extensive operational testing and validation. Slight structural redesign of the tug modules is necessary to allow one to operate at each end of a Mir module, avoiding solar panels blocking each other during maneuvering, with the modules central axis perpendicular to the ecliptic plane during the ion maneuvering phases of the mission. Use of one longer solar panel per tug instead of two shorter ones accomplishes this goal, without redesign of the systems or significant bus modifications. This Option B thus allows alternative, lower risk module designs to be used, depending on the technical experience we derive over the next few years with the international space station. Selection of which module to pursue wouldn't have to be made for some time after the program is underway, so plenty of experience gained on other peoples operations budgets will be available prior to the choice.

The mission operational plan is relatively simple. The manned campaign begins with a precursor flight, with one (two in Option B) tugs carrying one tug each as payload flying out to Mars prior to the manned expedition launch and one (two in Option B) tugs bringing an unmanned hab module. 2 years later, 6 months after the return tug has arrived, a manned module is launched with another one (or two) tugs with tugs as payloads. Trip time to Mars is about 18 months. The modules spiral in to close to Mars, coorbital with Phobos. On arrival, the manned module and the return vehicles "land" on the surface of Phobos, roughly at the Marsward pole. Once there, a simple base is set up: solar panels from available Tugs are connected to the base to provide power. The manned modules use batteries to provide power during the 4-hour Phobos nights. To avoid radiation health risks to the crews, one of the two modules is buried in the Phobos regolith, which is estimated to be up to 50 meters thick on average and should be relatively easy to dig into. The other module is left on the surface for use as the eventual return vehicle. After a short setup and settling in period, the primary exploration mission begins: utilizing multiple highly capable teleoperated rovers, operated with low (£ 0.1 sec) communications lag and thus highly responsive to the operators commands. With such low lag, relatively high speed of traverse and good ability to explore targets of opportunity are available.

The ground exploration program is organized to make as full as possible use of the crews. Two small comsats are placed 120 degrees behind and in front of Phobos in the same general orbit. These allow control of surface rovers anywhere on the planet. Assuming that rovers are operated only during local day and are solar powered, we can assume roughly 8 hours of useful operation per rover per day. With 2 crew on offset 8 hour work shifts we can keep rovers roving about 16 hours a day. With reasonably simple modern autonavigation rovers can be ordered from point to point semi-autonomously, with the operator intervening in tricky terrain or overriding based on science targets of opportunity that present themselves. Though operational testing will have to be performed to confirm predictions, it appears that one operator can safely command four such semiautonomous rovers operating at speeds up to 0.5 m/s in clear terrain and 0.1 to 0.25 m/s in rocky terrain, though this will vary depending on the time spent examining science targets. If local area science data collection can be effectively automated (rocks and soil areas selected by the operator for close visual inspection, neutron spectrometer readings, soil sample collection etc) then the operator can multiply this operational stable somewhat, with rovers spending large fractions of their time in local area characterization and only needing active operator oversight during traverses.

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One important key will be having a large science team on Earth backing up the automated data collection systems and Phobos-based human operators. Real time or near real time analysis and feedback to the system operator will greatly magnify the effectiveness of the mission. With time delays of 10 to 30 minutes between Mars surface data collection and real-time feedback from the Earth ground science team, it will be relatively easy to select targets of opportunity during area characterizations but difficult during traverses (during which time a rover would move at least 60 and up to 900 meters, making return to spotted targets costly). The Phobos based operator thus must keep close track of the environment around traversing rovers and locally identify interesting science targets in real-time. A small multiple (3 is assumed) of the traversing rovers is assumed for total rovers operational at any one time, giving us 12 rovers scattered over a third of the planet, or roughly 36 active rovers over the whole planet (most inactive due to daylight considerations at any one time).

With 20kg rovers and typical descent systems this gives us 40kg Mars orbit payload delivered per rover, or about 1.4 tons for the whole mission set. That assumes that rovers last for the entirety of the manned tour, which is probably optimistic. In all probability, the rovers will last for perhaps 6 months before suffering mechanical failure or getting stuck or overturned. A complete mission set at nominal full operational capacity would thus be about 4 times the daily operational number, or about 150 rovers (6 tons worth). One tactic that may make sense is to employ lightweight low-capabilities microrovers in large numbers, and to land larger more capable rovers at sites selected based on microrover data. In this scenario, 5-kg microrovers with cameras and perhaps neutron spectrometers (10 kg mars orbital payload) would provide 120 of the 150 rovers, with the remaining 30 being the larger more capable models with additional instrument packages, for a total delivered rover payload of 2.4 tons.

Taking this idea further, specialized rover types for certain environments could be developed: dual rovers with tethers, for exploring cliffs and valley sides, or rovers with anchors or convenient rock tiedowns and tethers; highly mobile rovers for examining broken terrain; generic rovers for relatively flat surfaces; etc. Some rovers could be designed for heavy duty rock collection, drilling, and the like. Others could carry extensive biochemical testing equipment should signs of life be detected.

Cost for the first manned orbital mission using Option B and including 2 payloads worth of unmanned exploration equipment would total roughly $7.3 billion. This includes launching a Mir type module to GEO and 2 flights of Soyuz or similar capsules on Proton or EELV to GEO (avoiding crew exposure to the radiation belts in transit) to establish the GEO staging base and fly flight crews and base staff to it.

Second Mission

As the first Phobos crew arrives on station and begin to teleoperate Mars surface rovers, the second crew is launched and depart from Earth. They will arrive about 2 years later, as the first crew is finishing up their operational rotation. After assisting to install a second habitat within the Phobos regolith, the first crew depart for home. The second crew now have twice the habitable volume at Phobos, new rovers, and 2 years worth of exploration data. At this point, much of the surface will still not have been examined at the desired level even by microrovers, and an ongoing new areas exploration program will be a major priority. However, carefully targeted re-exploration of sites of interest will be an increasing priority.

Third Mission

As the second crew are arriving at Mars, the third crew depart earth. Rather than just one module and its 2 crew, this time 2 modules and 4 crew are sent. With them come rovers that have been designed with target areas and environmental data from the first crew's exploration taken into account, likely including the more highly specialized types described above. On arrival, they bury 2 more modules in the Phobos regolith and see the second crew off on their return flight. Now with 4 crew in residence, each with at least 100 m^3 of volume, the base is ready for managing 24-hour operations. Working in 2 shifts, day and night, and with the 2 crew on each shift alternating operator duties, the operator efficiency should increase significantly. This will be required to oversee the more complex drilling, excavating, climbing and descending on tethers type rover explorations likely to be the focus of the third crew's tour.

Initial Manned Program Summary

With three manned missions and one dedicated precursor over a total span of 12 years, we send a total of eight crew to spend a total of 16 man-years in Mars orbit doing teleoperated science with surface equipment. Using minimal new hardware R&D, the total initial program cost is roughly $18 billion. For this $18 billion we get at least 30 thousand man-hours of zero-delay teleoperated science and exploration, a cost of about a half million dollars per hour of exploration, with the total time being largely flexible if budget constraints intervene. The total annual program budget is around $1.5 billion, with peak annual expenditures roughly $3.2 billion in the most active third mission phase.

7.0 CONCLUSION

By trading off R&D costs with launch and active operational costs, we have demonstrated a current-technology manned Mars mission (albeit without a manned landing) that provides extensive exploration for a total mission cost under $20 billion for a multimission program and under $10 billion for the first manned mission. We do not have to land humans on the Martian surface to get many of the benefits of manned missions: a human teleoperator of a reasonably capable rover can guide operations in real-time with a nontrivial fraction of the efficiency that a spacesuited human might achieve. Utilizing low thrust solar-electric Ion propulsion and standardized tug modules can enable mass production of efficient transportation.