Chapter 16
MISSION STRATEGIES

Carol Stoker and Larry Lemke present the conference with their proposal for a Mars Airplane.

Many sessions were standing room only.

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NEW DIRECTIONS: REEVALUATING THE LUNAR REFUELING OPTION

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Recent discoveries in the fields of Planetary Science and Astronautics hold exciting promise of potentially further optimizing future voyages from Earth to Mars. The existence of substantial water ice deposits at the Lunar poles, discovered by the *Clementine* mission and confirmed by the *Lunar Prospector* mission, in conjunction with the invention of the Belbruno-Miller Transfer, which significantly reduces the ΔV required to go from the Earth to the Moon, justify a reexamination of the possible merits of refueling in Lunar orbit en route to Mars. While the investment in infrastructure required in order to make refueling in Lunar orbit possible would be so substantial that it would be difficult to justify on the basis of a limited number of flights, if a permanent base or colony is to be established on Mars the synergistic advantages of Lunar refueling become more persuasive.

INTRODUCTION

Refueling in Lunar orbit en route to Mars has often been advocated in the past, however it has been less than certain that the advantages involved in Lunar Refueling would justify the increased complexity and cost of the infrastructure that would be necessary to develop in order to make it possible. Recently some things have changed; we have learned more about the Moon and about Orbital Mechanics. We now know that both hydrogen and oxygen exist in substantial quantities on the Moon. The ice deposits at the Lunar Poles, first discovered by the *Clementine* Mission and confirmed by the *Lunar Prospector* Mission, are one of the most exciting discoveries of the present decade. The existence of between 10 to 300 million metric tons of water ice[1] on the Moon significantly alters the equation. Complete refueling is now at least in theory possible. We also now know that it is possible to reach Lunar orbit using significantly less DV than was previously thought possible. The Belbruno-Miller Transfer,[2] developed by E. A. Belbruno and J. K. Miller of JPL, requires less DV than a Hohmann Transfer. Hohmann Transfers are typically assumed to minimize the DV required, however that is not always entirely true. Hohmann Transfers are based upon a two-body assumption and employ the technique of patched conics to enable the two-body assumption to be used in generating a more or less accurate approximation of systems that involve more than two bodies. Whereas the Belbruno-Miller Transfer takes into account the gravitational effects of the Earth, Moon and Sun on the spacecraft. Ballistic Capture into Lunar orbit is achieved by reaching the lunar weak stability boundary[3] and then applying a minute amount of DV to traverse this region to acquire a more stable orbit about the Moon, and finally to apply a small additional amount of DV to circularize the orbit. The Belbruno-Miller Transfer trades time in exchange for DV. While greatly increasing the flight time, from 5 to 180 days, it reduces the DV required to reach Lunar orbit by app. 25%.[4] The Belbruno-Miller Transfer from the Earth to the Moon, first demonstrated by the Japanese *Hiten* Mission, can help in not only reducing the DV required to voyage from Earth to Mars, but also to bring those deposits of water ice more within our reach.

REFUELING IN LUNAR ORBIT

Oxygen, in the form of silicates, is quite abundant on the Moon, composing approximately 42% of the Lunar regolith.[5] Previous proposals for partial refueling in Lunar orbit using, rely on this fact. Perhaps the most critical recent discovery in support of the argument in favor of refueling in Lunar orbit en route to Mars, is the discovery of the existence of water ice at the Lunar poles which could enable refueling of both hydrogen and oxygen. It is certainly true that the water, while it exists in large quantities, is not abundant and indeed is about three times rarer at the Lunar poles than it is in the equatorial regions of Mars.[6] Nevertheless it still ought to be possible on the Moon to use the same type of technology used to extract water on Mars although it will be more difficult.

The other key enabling advance is the development of the Belbruno-Miller Transfer. The Belbruno-Miller transfer centers on the Weak-Stability-Boundary (WSB) and a gravity assist maneuver around the Moon. It focuses on trying to spend the least amount of DV in its n-body (rather than the more common two body) assumption. “The orbit dynamics associated with the Weak-Stability-Boundary (WSB) method are related to the solar tide.[7]” The complexity due to this as well as the Stability-Boundary (SB) existing in six-dimensional position-velocity space complicates mission design yet there are distinct advantages to using the Weak-Stability-Boundary (WSB) technique.[8] “At the Earth’s Weak-Stability-Boundary (WSB) the dynamic effects of the Earth and Sun tend to balance. Thus, small maneuvers can cause large changes in the trajectory.[9]” In other words one can use less energy at the Weak-Stability-Boundary (WSB) to make a change that elsewhere would require more energy. The savings in DV by doing this is an admirable quality for the Weak-Stability-Boundary (WSB) especially considering that the classic approximation of the Hohmann Transfer was commonly considered the minimal DV for trajectories between two bodies in space. Though as mentioned before the length of time used in executing this type of trajectory is a concern. One would certainly not recommend a manned flight using this type of trajectory, yet if used only for cargo it should be considered a viable option.

The most promising potential application of refueling in Lunar orbit is to shorten the flight time of manned missions to Mars while also reducing the DV required (from Earth). If we want to study the effects of long duration spaceflight or any number of phenomena associated with zero-g then we can send the astronauts (and/or cosmonauts) to the International Space Station; if we want to explore Mars then we need astronauts (and/or cosmonauts) on Mars. If we are going to go to the trouble of sending astronauts (and/or cosmonauts) to Mars then we should wish to reduce the flight time en route to Mars as much as proves practical and cost effective, since the astronauts' (and/or cosmonauts') time is much better spent and more profitably employed on Mars rather than in space. While minimizing the DV (from Earth) is critical to containing costs, if the infrastructure exists to obtain hydrogen and oxygen from the Moon and to transport it to and store it in Lunar orbit then the substantial cost involved will be the creation of that infrastructure. Once that infrastructure is itself in place the actual cost of transporting from the Lunar surface to Lunar orbit the fuel needed to produce more than the minimum amount of DV required to go from the Moon to Mars should be perhaps almost nominal. Since transporting some mass from the Lunar surface to Lunar orbit requires less than one-twentieth the energy, due to the Moon's shallower gravity well and lack of an atmosphere, it would to transport that same mass from the surface of the Earth to Earth orbit; so that doubling the amount of fuel sent to orbit from the Moon would cost the same amount of energy as increasing by only 5% the amount of fuel sent to orbit from the Earth. Having rendezvoused and refueled in Lunar orbit, why not fill up the spacecraft's fuel tanks and use the excess fuel to decrease its time of flight to Mars rather than simply to fill the tanks with the minimal fuel necessary to reach Mars within 180 days?

Most mission designs now call for app. 180 day time of flights to Mars from Earth orbit, i.e. Mars Direct. Such a Fast Transfer from Low Earth orbit of 150 km (81 nmi) to Mars would require app. 3.76 km/s (12,345 ft/s) of DV, and can be used as a baseline for the sake of comparison to mission designs that incorporate refueling in Lunar orbit. Assuming the infrastructure exists to support refueling in Lunar orbit, it would be possible to further conserve the DV required (from Earth) by employing a Belbruno-Miller Transfer to travel from Low Earth orbit (LEO) to Lunar orbit. The Belbruno-Miller Transfer would require only 3.45 km/s (11,329 ft/s) of DV (from Earth), if the DV required from the Moon to Mars is neglected (taking the refueling DV costs in Lunar orbit as an expense of the maintenance of infrastructure) then the savings in DV (from Earth) would be approximately 8.23%. The Belbruno-Miller Transfer with its app. 180 day time of flight is obviously unsuitable for manned missions, however the crew composes only between 1 to 2% of the payload of a mission to Mars (using the "Mars Direct" mission design as a baseline). One possible mission design would be to launch the Mars mission spacecraft earlier via a Belbruno-Miller Transfer to Lunar orbit to refuel and have the crew travel in a small shuttlecraft, i.e. perhaps a modified X-38 or Soyuz spacecraft, from Low Earth orbit to Lunar orbit and then rendezvous with the Mars mission spacecraft. Such a mission design, in which the Mars mission spacecraft would execute a Belbruno-Miller Transfer from app. 150 km (81 nmi) Low Earth orbit (LEO) to app. 100 km (54 nmi) Lunar orbit, would result in a total DV of app. 3.45 km/s (from Earth) and assuming its fuel tanks were completely refueled - a time of flight (TOF) of app. 158 days from Lunar orbit to Mars. The crew would travel to the Moon via shuttlecraft thus resulting in a total time of flight from Earth to Mars (for the crew) of app. 163 days, an approximate 9.2% savings in time of flight (TOF) in comparison to 180 day time of flight from Earth orbit to Mars.

Another option that ought to be very seriously considered is increasing the size of the fuel tanks of the mars mission spacecraft beyond what would be required to store the fuel necessary to go from the Earth to the Moon. Then additional fuel could be transferred to the spacecraft when it refuels in Lunar orbit allowing it to execute a longer burn and further reduce its time of flight from the Moon to Mars. This would clearly involve a trade-off; increasing the mass of the fuel tanks in exchange for further reducing flight time. Such a decision would depend upon a number of factors which would ultimately dictate the optimal compromise between increased fuel tank mass and reduced flight time, chief among them the degree to which it would be possible to use composites or new alloys (such as Aluminum-Lithium) to increase the size of the fuel tanks without increasing their mass excessively. If we were able to significantly increase the volume of the fuel tanks we could more effectively exploit the advantages of flying out of the gravity well of the Moon rather than that of the Earth, to dramatically reduce time of flight to Mars from the Moon. For example if we were to increase the volume of the fuel tanks of the mars mission spacecraft simply by 10% in excess of what was required to execute a Belbruno-Miller Transfer from the Earth to the Moon (about the volume of fuel tanks required to execute a 180 day fast transfer from Earth orbit to Mars), it would be possible to reduce the time of flight to app. 159 days, a savings of app. 11.3%. If we were to increase the volume of the fuel tanks of the mars mission spacecraft simply by 25% in excess of what was required to execute a Belbruno-Miller Transfer from the Earth to the Moon then it would be possible to reduce the time of flight to app. 155 days, a savings of app. 14.1%. If we were to increase the volume of the fuel tanks of the mars mission spacecraft simply by 50% in excess of what was required to execute a Belbruno-Miller Transfer from the Earth to the Moon then it would be possible to reduce the time of flight to app. 147 days, a savings of app. 18.5%. If we were to double the volume of the fuel tanks of the mars mission spacecraft in excess of what was required to execute a Belbruno-Miller Transfer from the Earth to the Moon then it would be possible to reduce the time of flight to app 134 days, a savings of app. 25.6%, about two months.

DRAWBACKS TO LUNAR REFUELING

There is a drawback to such fast transfers from Lunar orbit to Mars. There is a limit to the velocity at which a spacecraft can safely aerobrake in the Martian atmosphere and therefore not all of the fuel obtained in Lunar orbit could be used to impart DV in a single firing of the engines in Lunar orbit. It would be necessary to conserve a certain amount of the fuel so that a second DV could be imparted upon reaching Mars in order to slow the velocity of the spacecraft with respect to Mars so that it could safely aerobrake in the Martian Atmosphere. It should be noted that the introduction of the second DV at Mars adds an additional failure mode - if the engine did not fire or if there were to be a major fuel leak, anything in short that prevented that second DV from being applied then the spacecraft would enter the Martian atmosphere at too high a velocity to effectively and safely aerobrake and entry at such a high velocity would result in the incineration of the spacecraft and its occupants. The probability of such failures however ought to be extremely low, nevertheless it goes without saying they are something to consider and evaluate very seriously.

Another drawback to refueling in Lunar orbit en route to Mars is the issue of launch windows. It is easier to reach Mars from Lunar orbit than from Earth orbit. There are two reasons for this; first, that the spacecraft is escaping chiefly from the Moon's and not the Earth's gravity well, which is deeper, and second, that the Moon revolves around the Earth. The Moon's revolution about the Earth is advantageous since less DV is required to go from Lunar orbit to Mars if the spacecraft fires its engines at the right time, since then the Moon's orbital velocity (1.026 km/s) about the Earth can along with the Earth's orbital velocity (29.790 km/s) about the Sun be subtracted from the perihelion velocity that the spacecraft must achieve in order to travel along its trajectory to Mars. Unfortunately, the Moon's revolution about the Earth also restricts the available launch windows. The Moon's orbital motion about the Earth dictates that the required DV from Lunar orbit will approximate a sinusoidal wave superposed on the curve representing the DV required to go from Earth orbit to Mars as a function of time, so that the launch window is shorter (less than a week) and opens two to three times each time a launch window from Earth to Mars occurs.[10] These shorter launch windows are naturally something that will have to be considered, if refueling in Lunar orbit is incorporated into the mission design of future missions to Mars. Nevertheless the shorter launch windows ought not to constitute a major obstacle - since a mission to Mars is not something undertaken on the spur of the moment and there will be more than enough time beforehand to optimize the scheduled mission departure; although the shorter launch windows may prove to be something of a nuisance.

The cost of the infrastructure necessary to support refueling in Lunar orbit is extremely difficult (nearly impossible) to estimate with any real confidence. As the Apollo program, the Space Shuttle program, and the International Space Station program have repeatedly shown, initial cost estimates are not always entirely accurate. The most reliable method of accurately accessing costs is based on experience with similar projects in the past, and so there is an inherent difficulty in attempting to estimate the costs of something that has never been done before. It is true that we have already lived and worked on the Moon during the Apollo missions, however our experience is still very limited in this regard since the total man-hours spent on the Moon during those missions only amount to a few hundred hours. A reasonable estimate would probably be costs roughly of the same order of magnitude as missions to Mars minus the costs of initial Research and Development since modified “Mars Direct” hardware could be used. So the cost of developing the infrastructure to support refueling in Lunar orbit would probably be in the range of tens of billions of dollars. Developing such infrastructure justified solely on the basis of aiding the exploration of Mars would seem difficult to justify as being cost effective in the short run. However evaluated over its lifetime such infrastructure ought be prove cost effect and of great benefit to the exploration and eventual colonization of Mars. Suppose an annual budget of approximately 3 billion dollars for a decade allocated to developing the infrastructure necessary to support refueling in Lunar orbit, a not altogether unreasonable assumption. This money would be invested in infrastructure, which is going to exist for an extended period of time. If you assume a life span of about 50 years for this infrastructure then its cost could be depreciated over those years. Allowing for the cost to allot about 60 million dollars a year for this infrastructure, since the cost is being spread out over a period of 50 years. Then as each of the years go by the 60 million from the year before will be added in the cost to the current 60 million; so that the cost the second year would be 120 million, the cost the third year would be 180 million, and so on and so forth. After ten years the cumulative cost of the infrastructure for the purposes of accounting would only be 3.3 billion dollars while in actuality the investment in infrastructure will have received 3 billion dollars a year for ten years. This allows the accounting of the costs for a budget to be manageable. The costing at time of launch, with no realization that we are establishing an infrastructure for the future of space exploration, is short sighted. With the realization that cost should be spread over the useful life which would be in accordance with generally accepted accounting principles (GAAP) then we would expect that most of these cost to be spread over the useful life of app. 50 years or more.

We would not be returning to the Moon solely on the basis of the merits of refueling in Lunar orbit. The farside of the Moon is probably the best place in the inner solar system to conduct astronomical observations. The observations, thousands of times better than is possible today, that could be made from the farside of the Moon would represent a quantum leap in Astronomy and would perhaps yield the first pictures of Earth-like planets orbiting nearby stars.

CONCLUSION

The Moon should not be viewed as merely a distraction from Mars. Just as missions to Mars can lend hardware designs and experience to Lunar missions, so too can infrastructure developed on the Moon to exploit Lunar resources aid future missions to Mars. There are compelling reasons to go to Mars, and our first voyages to Mars may precede our return to the Moon, but it should not be forgotten that there are also compelling reasons to return to the Moon. If the development of Lunar infrastructure is neglected then it will not only be our goals on the Moon that will be short changed, but also a new direction in the design of missions to Mars which will be being ignored. The potential benefits to the exploration and eventual colonization of Mars of the utilization of Lunar resources and refueling in Lunar orbit should not be dismissed without careful consideration of their merits. The quickest way to Mars may be via the Moon.

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