PHOBOS / DEIMOS SAMPLE RETURN VIA SOLAR SAIL

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Abstract A sample-return mission to the martian satellites using a contemporary solar sail for all post-Earth-escape propulsion is proposed. The 0.015 kg/m^2 areal mass-thickness sail unfurls after launch and injection onto a Mars-bound Hohmann-transfer ellipse. Structure and payload increase spacecraft areal mass thickness to 0.028 kg/m^2. During Mars-encounter, the sail functions parachute-like in Mars's outer atmosphere to accomplish aerocapture. On-board thrusters or the sail maneuver the spacecraft into an orbit with periapsis near Mars and apoapsis near Phobos. The orbit is circularized for Phobos-rendezvous; surface samples are collected. The sail then raises the orbit for Deimos-rendezvous and sample collection. The sail next places the spacecraft on an Earth-bound Hohmann-transfer ellipse. During Earth-encounter, the sail accomplishes Earth-aerocapture or partially decelerates the sample container for entry into Earth's atmosphere. Mission mass budget is about 218 grams and; mission duration is <5 years.

INTRODUCTION: SCIENTIFIC JUSTIFICATION AND SAILCRAFT CONFIGURATION:

There are many mysteries concerning Mars's satellites. They appear to be low-albedo comet nuclei. But if this is true, how were they captured into near circular, low-inclination orbits around the red planet. If they are captured comet nuclei, they may be rich in volatiles that would be of great use to future martian explorers. Also, if we are serious about maintaining a long-term global civilization, we must learn a great deal about Earth-approaching comets since these objects occasionally slam into the Earth with catastrophic consequences. Phobos and Deimos are relatively easy members of this class to explore. Table 1 presents data regarding Mars and its satellites.[1]

The mission proposed here could clear up many mysteries regarding Mars and its satellites. Various phases of the proposed mission are presented in Figure 1. After Earth-escape and injection into a trans-Mars trajectory, a solar sail is utilized for Mars aerocapture and Deimos rendezvous and sample collection, Phobos rendezvous and sample collection, acceleration on an Earth-return and for Earth capture.

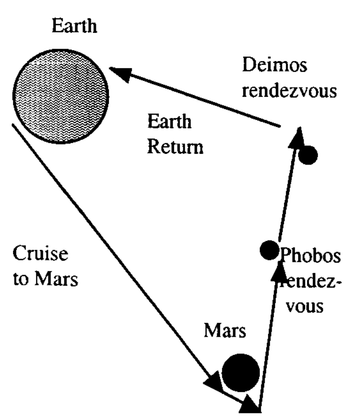
Table 1. Mars and its Satellites:

Mars

Mean equatorial radius = 3400 km
Mass = 6.42×10^{23} kg
Equatorial escape velocity = 5.03 km/sec
Average distance from Sun = 1.52 AU
Average solar orbit velocity = 24.13 km/sec

	Phobos	**Deimos**
semimajor axis	= 9378 km	23460 km
orbit eccentricity	= 0.015	0.0005
orbit inclination	= 1.02 degrees	1.82 deg.
size, km	= 13.5x10.8x9.4	7.5x6.1x5.5
mass	= 9.6×10^{15} kg	1.9×10^{15} kg
albedo	= 0.06	0.07
orbit period	= 0.32 days	1.26 days

Fig. 1. Mission Schematic



We next present (in Table 2) some details of the proposed spacecraft (s/c) configuration. We assume a very conservative sailcraft, in line with the recent technology review of Herbeck et al:[2]

Table 2: The Proposed Sailcraft

σ_{sail} = Sail areal mass thickness
= 15 g/m^2 = 0.015 kg/m^2
R_{sail} = sail radius = 50 m;
REF_{sail}= sail reflectivity = 0.9
Payload/structure mass (M_p) = 100 kg;
M_{sail} = sail mass = $\sigma_{sail} \pi R_{sail}^2$ = 118 kg
Spacecraft (s/c) mass = $M_{s/c}$ = 218 kg;
s/c areal mass thickness = $\sigma_{s/c}$ = 0.028 kg/m^2

LIGHTNESS FACTOR AND CHARACTERISTIC ACCELERATION AT EARTH and MARS:

We apply Eq. (4.19) of Ref.3 to calculate sailcraft Lightness Factor $\eta_{s/c}$:

$$\eta_{s/c} = 0.000787\ (1+REF_{sail})\ /\ \sigma_{s/c}. \quad (1)$$

Assuming a sail reflectivity of 0.9 and a sailcraft areal mass thickness of 0.028 kg/m^2, we obtain a sailcraft Lightness Factor of 0.053.

As described in Ref. 4, Lightness Factor = (solar radiation-pressure acceleration) / (solar gravitational acceleration). At the 1-AU Earth orbital distance from the Sun, the Sun's gravitational acceleration is about 0.0059 m/sec^2. Thus, the characteristic radiation-pressure acceleration of the sail oriented normal to the Sun at 1 AU is about 3.1×10^{-4} m/sec^2. At Mars' average solar distance of 1.52 AU, the sailcraft's characteristic acceleration is 1.34×10^{-4} m/sec^2.

EARTH-MARS TRANSFER

After insertion in a Mars-bound Hohmann trajectory, the duration of the one-way voyage to Mars is about 260 days.[5] The orbital energy of the Hohmann ellipse is written:

$$\varepsilon_{ht} = -GM_{sun}/(r_1 + r_2)\ \text{Joules/kg}, \quad (2)$$

where G = the Gravitational constant (6.67×10^{-11} MKS units), M_{sun} = solar mass =1.99×10^{30} kg, r_1 = the 1 AU (1.5×10^{11} m) perihelion of the Hohmann trajectory and r_2 = the 1.52 AU (2.28×10^{11} m) aphelion of the Hohmann trajectory. Substituting in Eq. (2), we find that $\varepsilon_{ht} = -3.51 \times 10^8$ Joules/kg.

The heliocentric velocity at Earth depatture is written:[5]

$$V_{ed} = \{2[(GM_{sun}/ r_1) +\varepsilon_{ht}\}^{-1/2}. \quad (3)$$

Substituting in Eq. (3), we obtain an Earth-departure heliocentric velocity of 32.68 km/sec, very close to the value in Ref. 5..

The heliocentric velocity at Mars arrival can be written

$$V_{ma} = \{2[(GM_{sun}/ r_2) +\varepsilon_{ht} \}^{-1/2}. \quad (4)$$

Substituting in Eq. (4), we obtain a Mars-arrival heliocentric velocity of 21.50 km/sec. Table 1 lists Mars' average heliocentric velocity as 24.13 km/sec, so the average relative velocity of the s/c and Mars at Mars arrival, V_{rm}, is 2.63 km/sec, which is in excellent agreement with the value in Ref. 4.

MARS AEROCAPTURE KINEMATICS

We next determine the velocity that the sailcraft must shed to be captured by Mars. From Eq. (4.12) of Ref. 3, the sailcraft's velocity relative to Mars at the start of aerocapture is $(V_{m,ex}^2 + V_{rm}^2)^{1/2}$, where $V_{m,ex}$ is Mars' escape velocity (5.03 km/sec). Substituting, we find that the s/c velocity relative to Mars at the start of aerocapture is $(5.03^2 + 2.63^2)^{1/2} = 5.68$ km/sec. To be captured as a satellite of Mars, the s/c velocity relative to Mars must be reduced by 5.68-5.03=0.65 km/sec.

Next, we refer to a 1996 finite element analysis which demonstrates that certain sail designs can sustain accelerations as high as 2.5 g (25 m/sec^2).[6] Conservatively, we constrain average aerocapture deceleration (ACC_{drag}) to 1 g (10 m/sec^2).

We calculate the velocity change during aerobraking using:

$$\Delta V_{dec} = ACC_{drag} t_{dec}, \quad (5)$$

where t_{dec} is the duration of the aerobraking pass. Substituting in Eq. (5), the aerobraking duration is about 65 seconds.We next relate the distance traveled during aerobraking, D_{dec}, to the average velocity during the aerocapture pass V_{av}:

$$D_{dec} = V_{av}\, t_{dec} = 348 \text{ km}. \quad (6)$$

Referring to Ref. 7 and applying the same logic as in our previous considerations of sail aerobraking,[8-10] we approximately relate average aerobraking deceleration (ACC_{drag}) to average s/c velocity during aerobraking (V_{av}), spacecraft areal mass thickness ($\sigma_{s/c}$), and the average density of the planetary atmosphere encountered during the aerocapture pass, ρ_{atm} :

$$ACC_{drag} = - \rho_{atm} V_{av}^2 / \sigma_{s/c}. \quad (7)$$

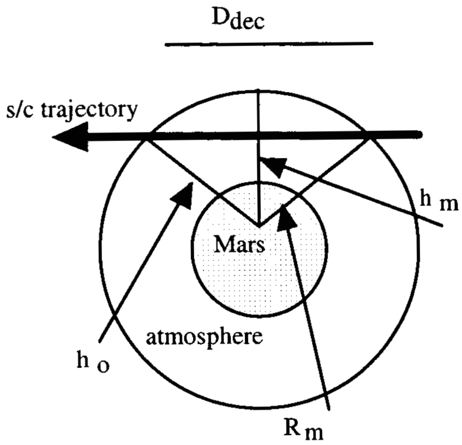
For an average drag deceleration of –10 m/sec^2, spacecraft areal mass thickness of 0.028 kg/m^2, and average aerocapture velocity of 5.36 km/sec relative to Mars, the average atmospheric density is about 9.8×10^{-9} kg/m^3.

Figure 2 presents a representation of the aerocapture pass. In that figure, Rm = Mars' radius = 3400 km, h_m = midpoint height of aeropass above Mars' surface, h_o = s/c height above Mars surface at start and end of aeropass, and D_{dec} = aeropass pass length (348 km).

We apply the Pythagorean relationship to the situation in Fig. 2 and require that $R_m >> D_{dec}/2$. Expanding and rearranging, we obtain the approximate relationship:

$$h_o - h_m = D_{dec}^2 / 8(h_m+R_m). \quad (8)$$

Fig. 2. Mars Aeropass Geometry



MARS ATMOSPHERE DENSITY PROFILE

Lodders and Fegley tabulate a density profile of Mars' atmosphere from 0-100 km that was derived using Viking 1/2 data.[1] . We investigated the validity of this profile for greater heights above the planet's surface. Our source for this phase of the analysis was a paper by Keating et al that compares in situ martian atmospheric density profiles in the height range 110-140 km above the planet's surface for Mars Global Surveyor (MGS), Pathfinder (P), Viking 1 (V1) and Viking 2 (V2).[11]

A good match to the Lodders and Fegley (LF) Mars atmosphere density tabulation between heights of 50 and 100 km can be had using the equation:

$$\rho_h = 1.19 \times 10^{-6} \exp[-(h-50)/7.52] \text{ kg/m}^3, \quad (9)$$

where h is the height above the surface in kilometers. The denominator of the exponential function, 7.52, is the density scale height H, in km. From the above discussion, the average Mars atmospheric density during the aerocapture pass is 9.8×10^{-9} kg/m^3. This corresponds to a height above the surface of 86 km.

Table 3 compares the extrapolation of the Lodders and Fegley tabulation with the atmospheric density values in Keating et al.[1,11] Keating's densities are at least 10X greater than the corresponding Lodders and Fegley values.

Table 3. Mars Atmospheric Density at 120-140 km Above the Surface:

ρ_h, kg/m^3

h, km	MGS,V1	V2	P	LF
120	10^{-8}	10^{-8}	10^{-8}	10^{-10}
130	4×10^{-9}	2×10^{-9}	9×10^{-10}	3×10^{-11}
140	10^{-9}	10^{-9}	2×10^{-10}	7.5×10^{-12}

The MGS, V1 and V2 Mars atmosphere density data in Table 2 can be approximately fit using the equation:

$$\rho_h = 10^{-8} \exp[-(h-120)/8.69] \text{ kg/m}^3. \quad (10)$$

All of these spacecraft yield a height above the surface of about 120 km for our average aerocapture pass density of 9.8×10^{-9} kg/m^3. The density scale height between 120 and 140 km is 8.69 km.

It is perhaps not surprising that different instruments in different spacecraft should reveal varying Mars atmosphere densities at different times. As Krasnopolsky and Feldman have revealed,[12] using Far Ultraviolet Explorer results, the Mars atmosphere H_2 density can vary by a factor of 10X or more between heights of 100 and 300 km. Interestingly, the shape of the density vs. height profile in their analysis is relatively constant. The solar-activity cycle seems to be the main factor controlling these variations, but Mars seasonal changes should not be ruled out.

Now we return our attention once again to the geometry of the Mars aerocapture pass. We substitute in Eq. (8) using h_m = 120 km, D_{dec} = 348 km, and R_m = 3400 km:
$h_m - h_o$ = 4.30 km. This is considerably less than the density scale height, H, which is between 7.52 and 8.69. Therefore, the isodensity model applied here works and, at least from a kinematics point of view, Mars aerocapture by solar sail is feasible.

THERMAL ASPECTS OF MARS SAIL / AEROCAPTURE:

We must still demonstrate that current technology solar sails can withstand the thermal stress of an aerocapture encounter with the martian atmosphere. As argued in Refs. 8-10, the most likely consequence of the interaction between a sail and martian atmospheric molecules will be sail heating.

It is assumed that all of the kinetic energy reduction of the sailcraft during aerocapture will be manifested as sail radiant energy. The change in s/c kinetic energy during aerocapture is expressed:

$$\Delta KE = 1/2\, M_{s/c}\, (V_{s/c,i}^2 - V_{s/c,f}^2), \qquad (11)$$

where $M_{s/c}$ is the spacecraft mass (218 kg), $V_{s/c,i}$ is s/c velocity relative to Mars at the start of aerocapture (5680 m/sec) and $V_{s/c,f}$ is the velocity of the spacecraft relative to Mars at the end of the aerocapture maneuver (5030 m/sec).

The average electromagnetic power radiated by the sail during aerocapture is the change in kinetic energy during aerocapture divided by the duration of the aerocapture pass (t_{dec} = 65 sec). The sail will radiate electromagnetic power from both sail faces. Assuming a disc sail architecture (radius R_{sail} = 50 m), sail irradiance is expressed

$$W_{sail} = \Delta KE / (2 t_{dec} \pi R_{sail}^2) = M_{s/c}(V_{s/c,i}^2 - V_{s/c,f}^2)/(4\, t_{dec} \pi R_{sail}^2). \qquad (12)$$

Substituting in Eq. (12), we obtain W_{sail} = 744 watts/m^2= 0.0744 watts/cm^2.

With McGinnis,[4] we assume a sail emissivity (ε) of 0.6. Applying a GEN-15C Radiation Calculator,[13] we obtain a sail radiation temperature (T_{rad}) of about 385 Kelvin. This can be checked using the standard version of the Stefan-Boltzmann equation:

$$W_{sail} = \varepsilon\, \sigma\, T_{rad}^4, \qquad (13)$$

where σ is the Stefan-Boltzmann Constant (5.67 X 10^{-8} MKS units). Substituting in Eq. (13), we obtain T_{rad} = 385 Kelvin. This value of sail radiation temperatures during Mars aerobraking will not tax existing sail designs.

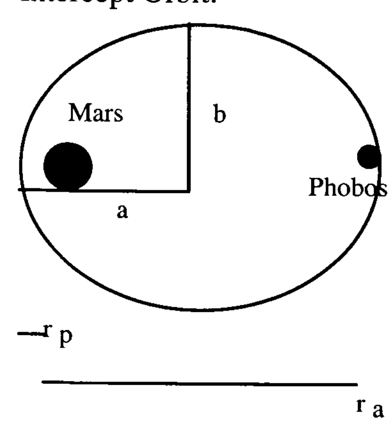
FEASIBILITY OF MARS-AEROBRAKING BY SAIL :

We see no obstacles to application of near-term solar-sail technology to performing an aerocapture maneuver in the martian atmosphere. An isodensity approximation for Mars' atmosphere is adequate, at least for screening purposes. A one-gravity average deceleration is reasonable to affect Mars aerocapture, with an estimated closest approach to the planet of about 120 km. Sail heating during Mars aerocapture is well within the capabilities of present-day solar sail materials.

THE PHOBOS-INTERCEPT ORBIT :

After its aerocapture encounter with Mars' upper atmosphere, the sailcraft is in elliptical orbit with Mars at one of the foci. Using the sail or a small on-board thruster, the orbit is adjusted so that the periapsis is just above Mars' atmosphere and the apoapsis is at Phobos. As shown in Fig. 3, a = orbit semi-major axis, b = orbit semi-minor axis,
r_p = periapsis distance = 3500 km. r_a = apoapsis distance = 9400 km.

Fig. 3. The Phobos-Intercept Orbit.



a = semi-major axis
b = semi-minor axis
r p =periapsis distance
r a =apoapsis distance

Note from Fig. 3 that $a = (r_a + r_p) / 2$. Applying an equation from Ref. 5, orbital eccentricity can be calculated:

$$\varepsilon_{orb} = (r_a - r_p) / (r_a + r_p) = 0.46. \quad (14)$$

The period of the Phobos-intercept orbit is calculated:[5]

$$P_{orb} = 2\pi\,(GM_{mars})^{-1/2}\,[(r_a + r_p)/2]^{3/2} = 15726 \text{ seconds}, \quad (15)$$

where M_{mars} = Mars' mass.

PHOBOS RENDEZVOUS :

The apoapsis velocity of the Mars-centered Phobos-intercept orbit can be calculated using:[1]

$$V_{ap} = 2\pi\,[(r_a + r_p)/2]\,P_{orb}^{-1}\,[(1-\varepsilon_{orb})/(1+\varepsilon_{orb})]^{1/2} = 1.567 \text{ km/sec.} \quad (16)$$

We next calculate Phobos' orbital velocity using the data in Table 1 :

$$V_{ph} = 2\pi R_{ph}/P_{ph} = 2.130 \text{ km/se}, \quad (17)$$

where R_{ph} = semi-major axis of Phobos' orbit (km) and P_{ph} is Phobos' orbital period (days).

To rendezvous with Phobos, the s/c must increase its apoapsis velocity by 2130-1567 = 563 m/sec. The characteristic acceleration of the s/c at Mars, with the sail oriented normal to the Sun ($ACC_{sail,mars}$), is 1.34×10^{-4} m/sec^2. Since the sail will not always be normal to the Sun, assume that the average acceleration during the Phobos-orbit-match maneuver is 6×10^{-5} m/sec^2. The time required to match match Phobos' orbit is therefore approximately $563 / 6 \times 10^{-5} = 9.4 \times 10^6$ sec. = 0.3 yr.

THE PHOBOS-DEIMOS TRANSFER

After gathering surface samples from Phobos, the Mars-centered orbit of the sailcraft is adjusted to accomplish a rendezvous with Deimos. Referring to the discussion on pp. 152-153 of Ref. 4, this can be accomplished by rotating the sail during its orbit so that for half the orbit the sail faces the Sun and for half the orbit the sail is edgewise to the Sun. The change in semimajor axis per orbit can be found using Eq. (4.90) of Ref. 4 :

$$\Delta a_{orbit} = 4\ ACC_{sail,mars}\ a^3 /(G\ M_{mars}) = 10.3 \text{ km/orbit}, \qquad (18)$$

which is the change in semi-major axis at the orbital height of Phobos. Since Phobos orbits Mars every 0.32 days, the sail can raise the orbit near Phobos by about 30 km /day.

Deimos is in a Mars-centered orbit with a semi-major axis of 23,460 km and an orbital period of 1.26 days. When the s/c is close to Deimos, the sail can increase the orbital semi-major axis by about 162 km/orbit or 129 km/day.

If we very conservatively assume that sail-position inefficiencies limit the orbit raising rate to only 30 km/day, the process will require 475 days or 1.3 years. The total duration of Phobos-Deimos exploration can therefore be estimated at 1.5-2 years.

DEPARTING THE MARS SYSTEM:

At this point of the mission, the sailcraft is orbiting Mars in a near-circular orbit at the orbital distance of Deimos. From Table 1, Deimos orbits Mars at a distance of 23,460 km once every 1.26 days. The orbital velocity of Deimos is $2\pi\,(23{,}460) / (1.26 \times 86{,}400) = 1.35$ km/sec.

The martian escape velocity from Deimos is 1.91 km/sec, since Deimos is in a near-circular orbit. To escape Mars from Deimos, the s/c must accelerate by 1.91-1.35 = 0.56 km/sec = 560 m/sec.

Assume as above that the average s/c solar radiation-pressure acceleration near Mars is 6×10^{-5} m/sec^2. The duration of the Mars-escape maneuver will be about 9.3×10^6 seconds or 0.30 years.

THE EARTH-BOUND TRANSFER

From Ref. 5, the Mars-bound and Earth-Bound legs of the Hohmann transfer ellipse will be symmetrical. Thus, after Mars escape, the sailcraft must reach a velocity of 2.63 km/sec relative to Mars for insertion into an Earth-bound Hohmann trajectory. At an average acceleration of 6×10^{-5} m/sec^2, the time required for this mission phase is 4.38×10^7 seconds or 1.39 years.

The return voyage to Earth along the Hohmann ellipse requires an additional 260 days, or 0.71 years. As it approaches the Earth, the sailcraft moves at a heliocentric velocity of 32.68 km/sec. From Ref. 1, Earth orbits the Sun at 29.79 km/sec. The s/c pre-Earth-encounter velocity relative to the Earth is therefore 32.68-29.79 = 2.89 km/sec.

MISSION DURATION:

Mission duration is estimated by summing estimates for various mission phases:

Earth-Mars transfer--	0.71 years,
Mars-Phobos transfer--	0.30 years,
Phobos-Deimos transfer --	1.30 years,
Mars-escape from Deimos --	0.30 years,
Earth-bound Hohmann insertion:	1.39 years,
Earth-bound transfer:	0.71 years.

The total mission duration is about 4.71 years. Mission duration might be less since some spacecraft mass could be jettisoned before Mars escape. A factor that could increase mission duration is postponement of Mars-departure maneuvers until Earth and Mars align appropriately.

EARTH AEROCAPTURE KINEMATICS

During Earth-approach, the Deimos and Phobos samples could be transferred to an atmospheric entry capsule that would then be jettisoned from the main sailcraft. Here, we investigate the option of keeping the samples aboard the sailcraft and utilizing the interaction of sail and Earth's upper atmosphere to accomplish aerocapture. The sailcraft, will thereby be captured as an eccentric Earth satellite.

The s/c approaches the Earth at 2.89 km/sec. From Ref. 1, the equatorial escape velocity of Earth is 11.18 km/sec. At the start of aerocapture, the s/c velocity relative to Earth is therefore $[(11.18)^2 + (2.89)^2]^{1/2} = 11.55$ km/sec. To be captured by the Earth, the sailcraft velocity relative to the Earth must be reduced by 0.37 km/sec.

We assume in this analysis that the post-aerocapture velocity is 11.15 km/sec, the velocity change during Earth-aerocapture (ΔV_{dec}) is 0.4 km/sec (400 m/sec) and the average velocity of the spacecraft during aerocapture (V_{av}) is 11.35 km/sec. Also, the spacecraft has the same configuration and mass as it did during Mars aerocapture and the average drag deceleration during Earth-aerocapture (ACC_{drag}) is limited to 1g (10 m/sec^2).

Dividing ΔV_{dec} by ACC_{drag}, Earth-aerocapture duration (t_{dec}) is 40 seconds. The distance traveled during aerocapture, D_{dec}, the product of V_{av} and t_{dec}, is 454 km.

If we substitute in Eq. (7) for a 10 m/sec^2 average Earth-aerocapture deceleration, an average aerocaptutre spacecraft velocity relative to the Earth of 11350 m/sec, a spacecraft areal mass thickness of 0.028 kg/m^2, we find that the average density of Earth's atmosphere encountered by the spacecraft during Earth-aerocapture ($\rho_{atm,earth}$) is 2.17 X 10^{-9} kg/m^3.

In Ref. 10, we present a curve-match to Earth's Standard Atmosphere that presents a reasonably accurate density profile in the height range 150-300 km:

$$\rho_{atm.earth} = 0.00056 \exp(-h_m / 13.16), \quad (19)$$

where h_m is the height of the midpoint of the aerocapture pass above the surface, in kilometers, and the density scale height (H) is 13.16 km. Substituting in Eq. (19) for $\rho_{atm.earth}$, we find that h_m = 164 km.

Applying Eq. (8), we can evaluate the accuracy of our isodensity atmosphere approximation by replacing Mars's radius (R_m) by Earth's radius (R_e). From Ref.1, R_e = 6371 km. Substituting in Eq. (8), we find the difference between the spacecraft height at the start and end of the aeropass (h_o) and h_m : $h_o - h_m = 3.94$ km. Since this is considerably less than the density scale height of 13.16 km, the isodensity approximation is valid. From a kinematical point of view, Earth aerocapture is feasible.

EARTH AEROCAPTURE THERMAL ASPECTS

Equation (11) is used to obtain the reduction in s/c kinetic energy during aerocapture: $\Delta KE = 10^9 (11.55^2 - 11.15^2) \text{ X } 10^6 = 9.9 \text{ X } 10^8$ Joules. Here, we approximate ΔKE as 10^9 Joules.

Sail irradiance is next approximately calculated from Eq. (12) to be 1592 watts/m^2. Applying Eq. (13) for a 0.6 emissivity sail, sail-radiation temperature is next determined as 465 degrees Kelvin. This result has been successfully checked with the GEN-15C Radiation Calculator[13]. Although thermal loading is greater for Earth aerocapture than for Mars aerocapture, Ref. 4 reveals that many current sail materials can sustain temperatures as high as 465 K.

CONCLUSIONS:

This analysis uncovers no obvious obstacles to flying a sample-return mission to the martian satellites using a contemporary solar sail as the principal post-Earth-escape propulsion system. The duration of such a mission can be less than five years.

Sail aerocapture by both Mars and Earth seems to be feasible. Possible issues still to be addressed include the effects of atomic oxygen in Earth's exosphere. But since Earth-aerocapture is the terminal mission phase and the sail could be expended as an Earth-atmosphere-entry aid instead of being used as an Earth-aerocapture system, sail life expectancy in Earth's upper atmosphere is of little significance.

Lodders and Fegley have discussed the photochemistry of the martian atmosphere.[1] Since Mars's atmosphere is predominantly CO_2, solar ultraviolet photons will slowly convert CO_2 to CO and O_2 and CO to C and O. The concentration of electronically excited atomic oxygen at 120-140 km above the martian surface is still to be investigated. But because of the high altitude and short duration of the martian aerocapture pass, photochemical constraints upon sail design seem unlikely.

Maneuvers in the martian system require the sailcraft to be rotated as it orbits Mars, thereby optimizing solar radiation-pressure acceleration. More research is required to determine whether such maneuvers require thrusters or can be accomplished using sail steering vanes.

Much work remains to be done on the optimization of interplanetary and aerocapture trajectories, the design of the spacecraft, and the development of protocols for sample retrieval and station keeping with the martian moons. However, this preliminary research has uncovered no serious mission show-stoppers.

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