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Hypersonic Maneuvering for Augmenting Planetary Gravity Assist

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In a previous paper, the authors analyzed aeromaneuvers at Venus and Earth. In this paper, they extend the study to Mars, examining the potential of aeroassist maneuvers at Mars for missions to the Sun and to Pluto, using a high lift/drag vehicle such as the waverider to perform an atmospheric fly-around of Mars, in order to rotate the planetocentric velocity vector, thus adding to the rather small rotation due to gravity alone. A fly-around in one direction or the other can place the aphelion or the perihelion of the resulting orbit at the Mars distance for missions toward the Sun or toward Pluto, respectively. The parameters of such maneuvers are given as a function of Earth launch velocity. It is found to be advantageous in terms of Earth launch velocity to perform two aeromaneuvers, e.g., one at Venus and then one at Mars. Some problems regarding the actual implementation of these aeromaneuvers are discussed.

Nomenclature

A = reference area of vehicle, m^2
C_D = drag coefficient
C_L = lift coefficient
C_3 = launch energy, km^2/s^2
$DV, \Delta V$ = velocity increment, km/s
i = inclination
m = mass of vehicle, kg
R = radius of planetocentric trajectory, km
V = velocity of vehicle, km/s
ρ = atmospheric density, kg/m^3
ϕ = arc length in atmosphere, rad

Subscripts

a = aphelion
c = circular orbit
E = Earth
esc = escape
J = Jupiter
M = Mars
P = Pluto
p = periapsis
S = Sun
s/c = spacecraft
V = Venus
∞, inf = relative to planet at infinity

Introduction and Background

PLANETARY gravity assist has been used successfully in many exploration missions in the solar system including the recent completion of the grand tour of the outer planets by the Voyager spacecraft. These missions have used the fact that energy can be transferred from a planet to a spacecraft when the spacecraft's trajectory is perturbed by the planet's gravity field. The effect of this perturbation is to rotate the planet centered spacecraft velocity vector, thus changing the direction and magnitude of the spacecraft's heliocentric velocity. The amount of change in the heliocentric velocity ΔV is simply related to the amount of rotation or bending caused by the planet. Very large changes in velocity are possible if this bending angle can be large. Unfortunately, few bodies in the solar system are massive enough to cause a sufficient gravitational perturbation to produce a large ΔV. Jupiter is one of these bodies and has been used successfully by the Pioneers and Voyagers to yield very high ΔVs enabling multiplanet flybys of the outer planet system. However, Jupiter is a remote planet, has a dangerous radiation field, and is a desirable planet for gravity assist only because of its large mass.

Historically, the terrestrial planets have been used to give ΔV values in the range of 3–5 km/s (e.g., the Galileo mission). However, missions such as Solar Probe or a five-year travel time mission to Pluto require ΔV values in the range of 10–25 km/s. This ΔV magnitude can be achieved using the terrestrial planets and aero-gravity-assist maneuvers. With the advent of the waverider hypersonic vehicle, large bending angles of a spacecraft's velocity vector are possible by flying through the atmosphere of a terrestrial planet. The resultant heliocentric velocity changes are much larger than gravity assist alone and can enable very high energy missions using the terrestrial planets, hence, the term aerogravity assist.

During Solar Probe mission studies early in the past decade, it was noted that the spacecraft configuration with its conical

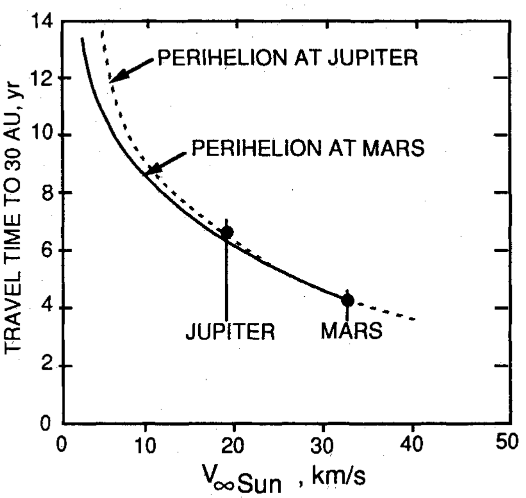

Fig. 1 Travel time to Pluto vs $V_{\infty S}$ relative to the Sun.

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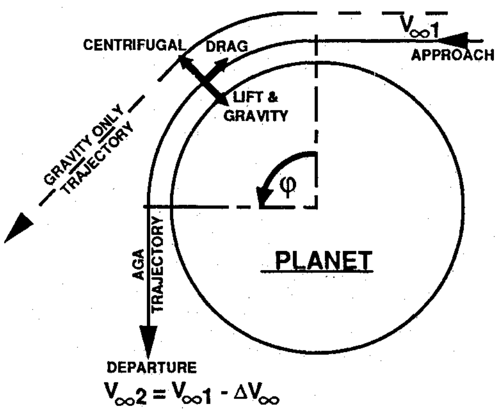

Fig. 2 Schematic of aero-gravity-assist maneuver.

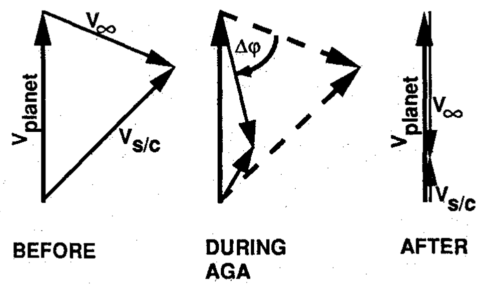

Fig. 3 Rotation of planetocentric velocity vector in an AGA maneuver for Solar Probe.

shield resembled an aerodynamic entry vehicle. This led to the thought that the vehicle could use a planetary atmosphere as an energy source to provide aero-gravity-assist (AGA) trajectories. After a brief analysis,[1] it was determined that extreme lift/drag L/D ratios (~ 10) would be needed to accomplish the maneuvers. It was clear that typical high drag entry vehicles ($L/D < 3$) could not be used.

In the 1950s while at Glasgow University, Nonweiler[2] introduced a new aerodynamic concept called a hypersonic waverider, which theoretically had very high L/D ratios ($L/D > 5$). A research group in Glasgow from the Association in Scotland to Research into Astronautics (ASTRA)[3] had been considering entry applications of Nonweiler's waveriders when we made contact with them in 1984. They were enthusiastic about applying this vehicle to the hypersonic velocity regime associated with AGA.

More recently, research into hypersonic waveriders optimized for viscous flow[4] has resulted in refined shapes and empirical data suggesting the reality of high L/D ratios at high Mach numbers. Further application of waveriders for planetary exploration was proposed by Lewis and Kothari.[5] They describe realistic drag losses and other characteristics of actual atmosphere passages that would affect the AGA maneuvers.

This paper augments the previous research by considering actual trajectories between planets using Mars as the final aero-gravity-assist planet.

Problem

Future interplanetary missions requiring high energy trajectories (e.g., Solar Probe and Pluto flyby) are currently planned to include a gravitational flyby of Jupiter either to rotate the planetocentric velocity vector of the spacecraft in a retrograde sense cancelling the heliocentric velocity of the spacecraft in order to go toward the Sun or to rotate in a direct sense adding to the spacecraft velocity in order to go toward Pluto. There are several disadvantages associated with these missions, including the following:

1) The Earth launch energy to go to Jupiter to arrive with sufficient speed is high. A C_3 [$=(V_{\infty E})^2$] of about 120 is necessary to achieve a $V_{\infty J}$ of about 13 km/s at Jupiter for a Solar Probe type mission to the Sun, and a high $V_{\infty J}$ is desirable for a reasonable travel time to Pluto (30 a.u.); e.g., the same $V_{\infty J}$ of 13 km/s at Jupiter (i.e., $V_{\infty S} \approx 18$ km/s) would give a Jupiter-Pluto travel time of about 6.8 years. [See Fig. 1, which shows the travel times to 30 a.u. from Jupiter (i.e., $V_{\infty S} = 18$ km/s) and Mars as a function of the solar system escape speed $V_{\infty S}$.]

2) A close pass of Jupiter to use the gravitational bending of the heliocentric velocity subjects the spacecraft to considerable electron and proton fluences, requiring hardening of electronic parts and/or shielding.

3) The Solar Probe trajectory period resulting from a Jupiter flyby is about 4.2 years; with a Earth-Jupiter-gravity-assist (EJGA) trajectory, the first perihelion pass would be about 5 years from launch and the second pass about 9 years.

4) Gravity-alone bending at the small planets is limited, calling for multiple flybys, long flight times, and limiting opportunities to times when favorable geometry exists.

The vertical lines in Fig. 1 show the special cases where $V_{\infty S}$ = heliocentric velocity of the planet, and the planetary maneuver places the perihelion at the planet. Vertical lines labeled Jupiter and Mars are the $V_{\infty S}$ at the orbits of Jupiter and Mars, respectively, for solar system escape.

Solution: Aero-Gravity-Assist Maneuver

The disadvantages just mentioned could be obviated by executing an AGA maneuver at Venus, Mars, or Earth. These planets are not large enough to rotate the planetocentric velocity vector by gravity alone as much as is necessary for a Solar Probe or Pluto type mission. However, a vehicle with sufficient aerodynamic lift, directed downward, could counter the centrifugal force and thus fly around the planet, exiting in the desired direction for either the Solar Probe or the Pluto destination. In a prior paper,[6] the authors considered AGA maneuvers at Venus and Earth. The present paper examines Mars as an AGA planet and finds that the main advantage over Earth and Venus is the reduced speed of the maneuver in the atmosphere.

It is noteworthy that the use of AGA maneuvers would free the mission designer from many of the present restrictions on launch date opportunities. Although the most effective use of AGA would seem to place either the aphelion or the perihelion of the resulting vehicle orbit at the planet exit point, the exit vector can clearly be varied to accommodate the real position of the next target planet. It will be seen later that there is a

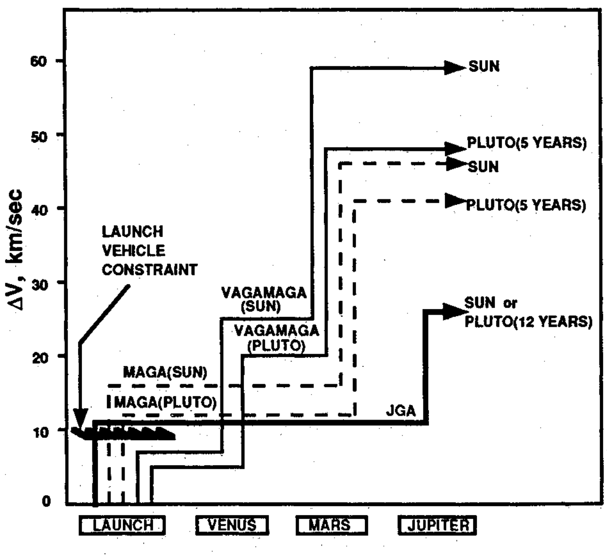

Fig. 4 Heliocentric velocity increments at each trajectory event.

Table 1 Aero-gravity-assist potential of the planets

Planet	Vehicle orbit inclination, deg	V_∞, km/s	V_p, km/s	Period, yr
	Solar probe at $4R_S$			
Venus	0	27.2	29.1	0.23
	90	35.2	37.3	
Earth	0	24.1	26.5	0.36
	90	30.3	32.3	
Mars	0	20.4	21.0	0.68
	90	24.4	24.9	
Jupiter	0	11.9	60.7	4.2
	90	13.1	61.0	
	Pluto flyby (five years from planet to Pluto)			
Venus	0	21.9	24.2	
Earth	0	20.8	23.6	
Mars	0	20.0	20.6	
Jupiter	0	20.5	63.0	

launch energy advantage in AGA maneuvers at two planets in succession, offset, of course, by the added navigational complexity. One can see that there would be tradeoffs in the amount of bending at the two maneuvers, the drag losses and possible correcting propellant burns, to maximize the payload at the final destination.

The AGA maneuver is simple in principle, as depicted in Fig. 2. A vehicle with a high aerodynamic lift flies a path in the atmosphere around a planet, at an altitude such that the lift force (directed downward) just balances the centrifugal force, so that the vehicle maintains nearly constant altitude. The drag force constantly decelerates the vehicle, so that the speed at exit will be less than the speed at entry to the atmosphere. However, with the waverider, the reduction in speed will be minimized. The vehicle exits when the correct departure asymptote is achieved.

Figure 2 illustrates that the gravity component of the bending is relatively small and that the final velocity $V_{\infty 2}$ (at exit) is less than the initial velocity $V_{\infty 1}$ and the atmospheric drag loss (ΔV_∞).

The approximate equation describing the balance between the aeroforce, centrifugal force, and gravity is

$$\frac{1}{2}\rho V^2 C_L A + mg = \frac{mV^2}{r} \tag{1}$$

from which one can find the atmospheric density, almost independent of the speed, at which the vehicle should fly

$$\rho = \left[1 - \left(\frac{V_c}{V}\right)^2\right] \frac{2}{R} \left(\frac{m}{C_L A}\right) \tag{2}$$

The loss of velocity due to drag can be found by integrating the drag through the atmosphere,

$$\mathrm{d}V = -\frac{1}{2}\rho V^2 \frac{C_D A}{m}\,\mathrm{d}t \tag{3}$$

to obtain, approximately,

$$\frac{\Delta V}{V} = -\frac{\phi}{(C_L/C_D)}\left[1 - \left(\frac{V_c}{V}\right)^2\right] \tag{4}$$

Using the relationship between $V = V_p$ and V_∞, we can write a slightly different drag loss equation:

$$\frac{\Delta V_\infty}{V_\infty} = -\frac{\phi}{(C_L/C_D)}\left[1 + \left(\frac{V_c}{V_\infty}\right)^2\right] \tag{5}$$

A note is in order about the assumptions and accuracies of these fundamental equations. In Eq. (1), V on the left is the air-relative speed and V on the right is inertial. For the inner planets at the speeds of interest here, the difference is small. Equation (4) assumes that V is constant and that the entry and exit portions of the atmospheric pass are a small part of the total; the arc ϕ is evaluated as the required bending minus the bending due to gravity alone. With these approximations, one would expect Eqs. (1-5) to be accurate to better than 10%.

The authors have estimated[6] that a vehicle with $m/C_L A = 50$ kg/m^2 would require an atmospheric density value of about 1.5E-05 kg/m^3 for Earth, equivalent to the standard atmosphere at 83-km altitude. The same vehicle at Mars (with a radius of 3460 instead of 6460 km) would require $\rho = 2.9$E-05 kg/m^3, i.e., a height of 61 km, well above the highest topography. For Venus, with a radius of 6150 km, the value of ρ would be 1.6E-05 kg/m^3, at an altitude of about 104 km.

The effect of the bending of the planetocentric velocity vector is illustrated in Fig. 3. For a Solar Probe mission, one wishes to bend the vector so that the exit V_∞ opposes the heliocentric velocity of the planet as shown, placing the aphelion of the resulting vehicle orbit at the planet. For a Pluto mission, one wishes the exit V_∞ to add to the heliocentric velocity of the planet, placing the perihelion of the resulting vehicle orbit at the heliocentric distance of the planet (not shown). Figure 3 illustrates the process of aerogravity assist at Mars depicting the initial, transition, and final stages of the process. The rotation of the planetocentric vector V_∞ through angle ϕ leads to the reduction of the heliocentric velocity $V_{s/c}$ to nearly zero. For a Solar Probe mission, the orbit is to be polar, i.e., inclination $i = 90$ deg relative to the Earth ecliptic. Then, in addition to canceling the heliocentric speed of the planet, one must give the vehicle at exit a small velocity normal to the ecliptic. For example, for the vehicle aphelion at Mars (1.5 a.u.), the velocity normal to the ecliptic is 3.29 km/s to

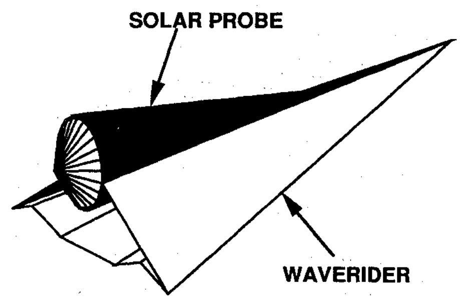

Fig. 5 Waverider-Solar Probe schematic.

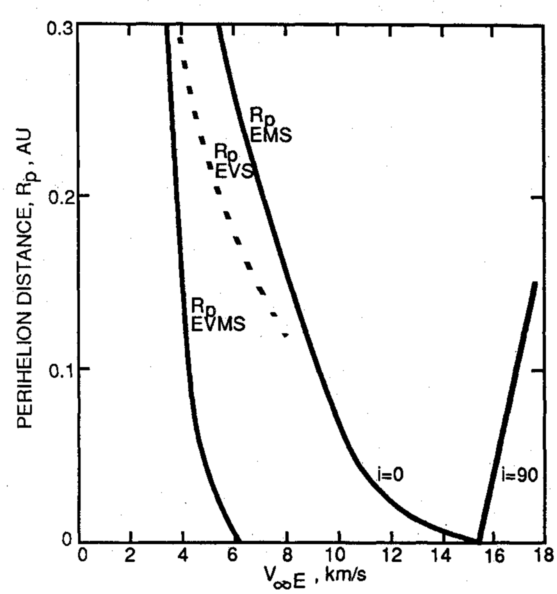

Fig. 6 Solar Probe perihelion distance vs Earth launch velocity.

Table 2 Solar Probe trajectory to $4R_s$

Trajectory	EVMS	
Inclination	0	90
$V_{\infty E}$	5.4	6.6
$V_{p,M}$	15.7	17.5

Table 3 Trajectories to Pluto

	Trajectory		
	EMP	EVMP	EVMP
Inclination, deg	0	0	0
MP travel time, yr	10	7	5
$V_{\infty E}$, km/s	6.4	4.2	5.9
$V_{p,M}$, km/s	12.7	16.0	22.5
$V_{p,V}$, km/s		13.6	16.4

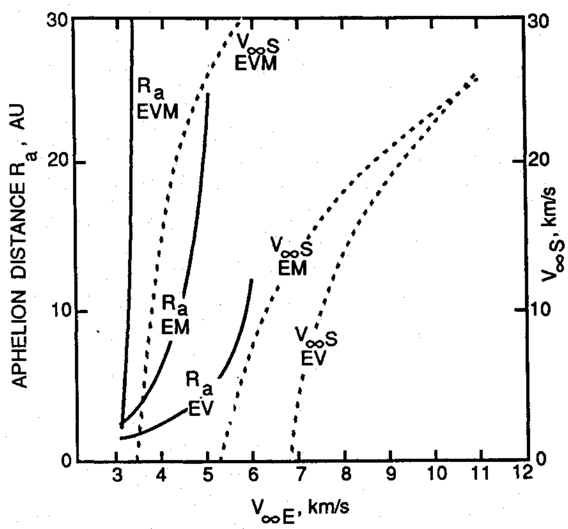

Fig. 7 Pluto aphelion distance vs Earth launch velocity.

give a perihelion distance of $4R_s$ or 0.0186 a.u. Thus, the V_∞ leaving Mars must be about 24.3 km/s, having a component of 24.1 km/s in the ecliptic (ignoring here the slight inclination of the Mars orbit) to cancel the heliocentric speed of Mars, and 3.29 km/s normal to the ecliptic to fix the perihelion ($4R_s$) of the vehicle's polar orbit.

Table 1 lists the planetocentric V_∞ and the periapsis velocity V_p values appropriate for Solar Probe and Pluto orbits at Venus, Earth, Mars, or Jupiter as the final planet. For Jupiter, as has been mentioned, the gravitational bending is enough so that the aeromaneuver is superfluous and the flyby would be done in vacuum above the atmosphere. However, a flyby of Jupiter has the disadvantages of radiation exposure, long travel time, and long final Solar Probe period. From Table 1, one can see that an AGA maneuver at Mars calls for considerably less speed and thus less heating than for Earth or Venus. For a Solar Probe mission with $i = 90$ deg, the periapsis (atmospheric) speeds at Mars, Earth, and Venus are about 25, 32, and 37 km/s, respectively. However, for a five-year mission to Pluto (five years from the Mars AGA to Pluto), the periapsis speeds at the planets differ less, being about 21, 24, and 24 km/s for Mars, Earth, and Venus, respectively, as the last AGA planet.

Another illustration of the AGA relationships for various missions is shown in Fig. 4 and is similar to an earlier analysis[7] of gravity-assist and low-thrust trajectories. Here, the ΔV imparted to the spacecraft's heliocentric velocity is plotted for each energetic event during the missions shown. Three types of trajectories are illustrated: 1) Jupiter gravity assist (JGA) (gravitational perturbation only), 2) Mars aerogravity assist (MAGA), and 3) Venus aerogravity assist followed by Mars aerogravity assist (VAGAMAGA). For each type, Solar Probe (labeled "sun" in the figure) trajectories are compared to the Pluto trajectories. Also shown is a launch vehicle constraint for typical Solar Probe or Pluto spacecraft. That is, with current launch vehicles, the spacecraft mass limits the launch V_∞ to about 9 km/s ($C_3 = 81$ km^2/s^2). Clearly, the JGA trajectory violates the launch constraint. Also, the MAGA trajectories require even higher launch energies and violate this constraint. In contrast, the VAGAMAGA trajectory has low launch energy but gains very large velocity increments at Venus and Mars resulting in immense total ΔV. These trajectories produce Solar Probe orbits with short final periods (0.7 years) and Pluto trajectories with short flight times (5 years).

Waverider Vehicle

The waverider is the name given to a hypersonic high lift/drag vehicle based on a principle suggested by Nonweiler[2] in which the vehicle shape is carefully chosen so that it appears to ride on the attached shock from its sharp leading edge, giving it high lift and low drag. In recent years, such shapes have been optimized[4,5] with the boundary layer included for applicable ranges of Mach and Reynolds numbers, and wind-tunnel tests have confirmed the shapes for laminar continuum conditions.

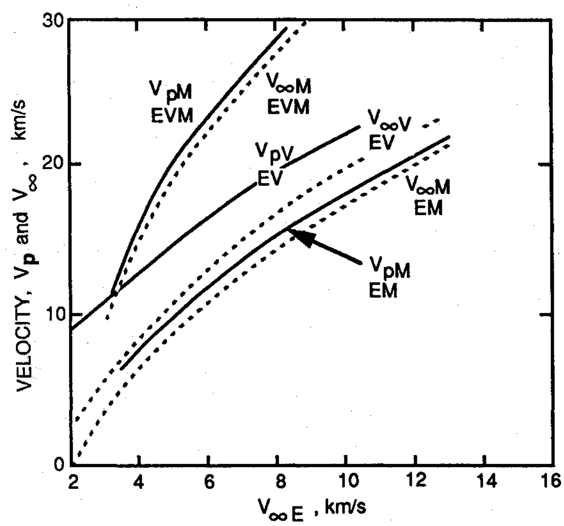

Fig. 8 Planetocentric velocities vs Earth launch velocity.

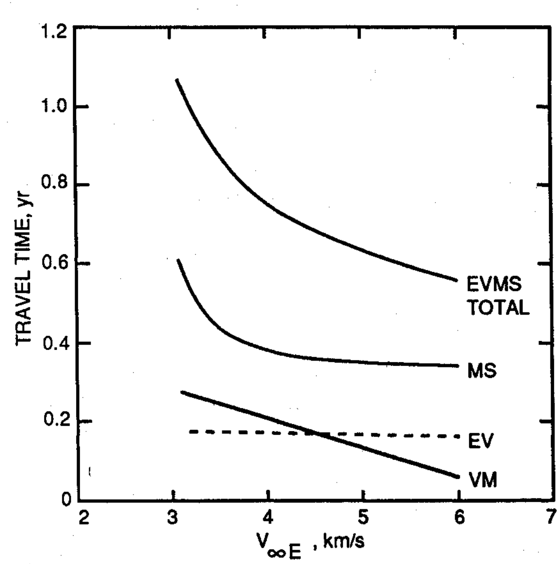

Fig. 9 Solar Probe travel time vs Earth launch velocity.

Table 4 Solar Probe trajectories ($4R_S$, $i = 90$ deg) from MIDAS data

Trajectory	Launch date	Planet	V_∞, km/s	Bend angle, deg	V_∞, ideal
EVMS	6-14-07	Earth	8.6		6.6
	8-10	Venus	17.5	79	
	10-23	Mars	24.8	83	
	3-20-08	Sun			
EMS	6-4-03	Earth	18.1		ideal 15.7
	7-20	Mars	26.4	115	
	10-22-03	Sun			

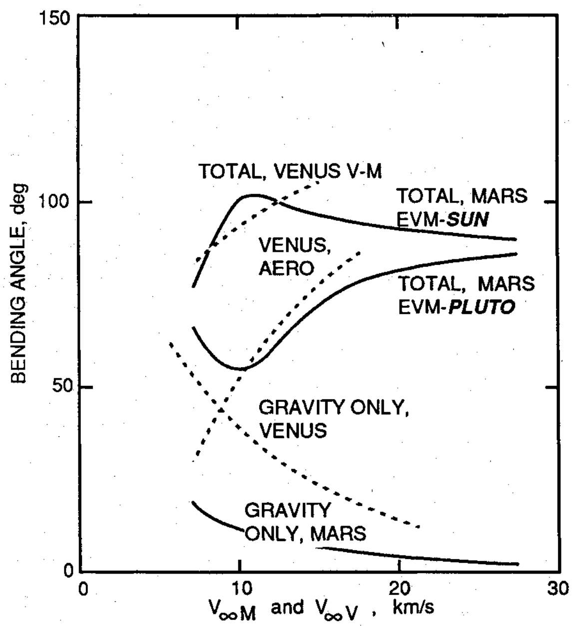

Fig. 10 Total bending angle vs planetocentric hyperbolic velocities.

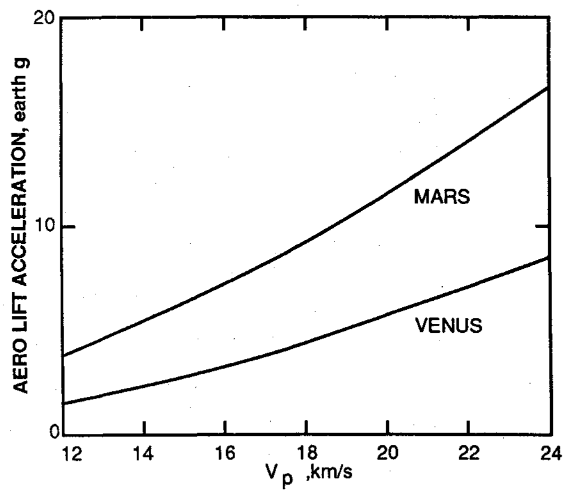

Fig. 11 Acceleration vs periapsis velocity.

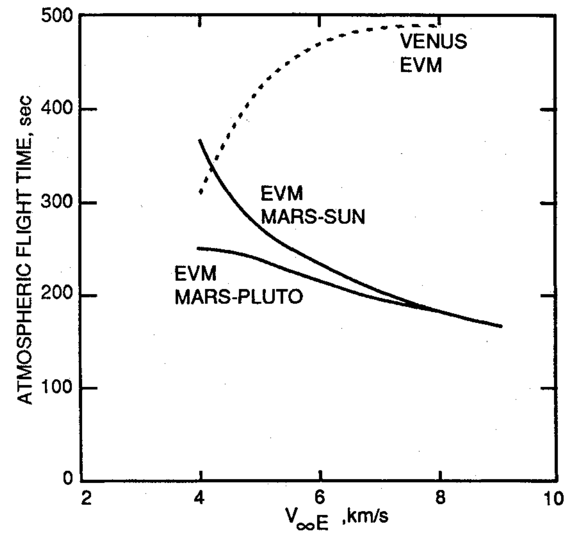

Fig. 12 Atmosphere flight time vs Earth launch velocity.

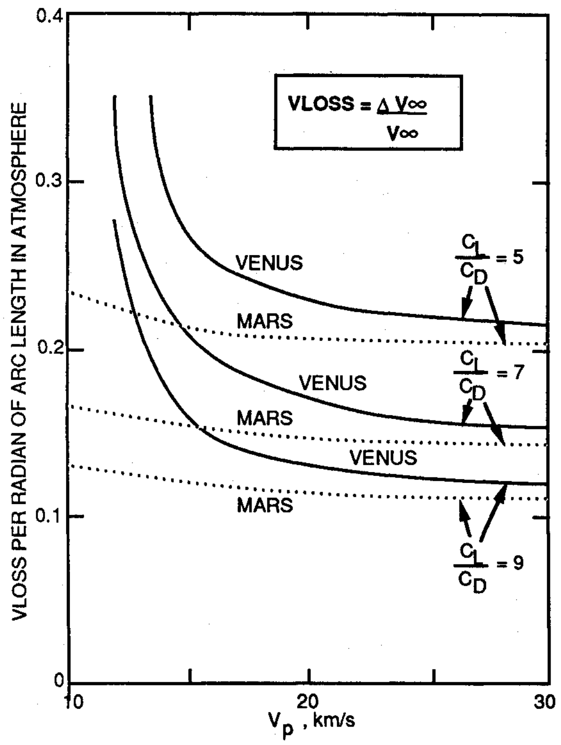

Fig. 13 Velocity loss during AGA vs periapsis velocity.

The waverider is a long slender vehicle with a sharp leading edge, as shown schematically in Fig. 5 for a Solar Probe mission. It has a swept-back curved wing, with a C_L of about 0.1 and a C_D of about 0.01–0.02, i.e., C_L/C_D of about 5–10, at a particular Mach number, over a few degrees of angle of attack in the range of 0–10 deg.

A vehicle for aeromaneuvers at these high speeds would be subject to severe leading edge and windward heating and considerable aero loads. Proponents of the waverider claim that it can carry a payload on the top surface, as shown, and that it can accept high heating rates by having slightly rounded leading edges, with a slight loss of L/D. No details are available on the loss of performance for a modified vehicle that has rounded leading edges, is less slender, wider, contains a payload packaged to locate the mass center forward of the center of pressure for aero stability reasons, and may have added conventional wing surfaces. These issues are significant and future research is required to establish whether the issues can be resolved to allow the AGA technique to be a reality.

AGA Maneuvers at Mars

The results of a study of AGA maneuvers at Mars are shown in Figs. 6–13. For these results, the simplifying assumption was used that Earth, Venus, and Mars are in coplanar circular orbits at their average heliocentric distance. For Mars, which has a much more eccentric orbit ($e = 0.09$) than the others, a calculation for Mars at aphelion was also done. Figure 6 shows the perihelion distance R_p that can be achieved in a Solar Probe type mission as a function of Earth launch velocity $V_{\infty E}$, for a Solar Probe orbit in the ecliptic ($i=0$), and a polar orbit ($i=90$ deg). Also shown are curves for only an aeromaneuver at Mars (Earth Mars Sun, EMS), for only an aeromaneuver at Venus (Earth Venus Sun, EVS), and for two sequential AGA maneuvers, one at Venus and then one at Mars (EVMS). Note that more velocity is required for the out of plane velocity component for $i=90$ deg trajectories. It is clear that the launch energy at Earth is much less for a given result if two AGA maneuvers are used.

Figure 7 shows similar curves for a Pluto type mission, i.e., a mission out from the Sun. The parameter shown is the aphelion distance R_a and then the heliocentric velocity at infinity $V_{\infty S}$ when the orbit becomes hyperbolic, as the launch energy is increased. The figure shows the aphelion distance that can be achieved, in an outer planet mission, by several trajectories, as a function of the initial Earth launch $V_{\infty E}$. The labels EVM, EV, and EM denote, respectively, the trajectories Earth + AGA at Venus + AGA at Mars, Earth + AGA at Venus, and Earth + AGA at Mars. As $V_{\infty E}$ increases, the R_a increases rapidly. The dashed curves show, for the same trajectories as before, the heliocentric hyperbolic velocity $V_{\infty S}$ leaving the last planet. From Fig. 7, one can see that a desired $V_{\infty S}$ can be achieved for less $V_{\infty E}$ with the EVM trajectory than with the EM trajectory and that the EM trajectory is better than the EV trajectory. For example, a $V_{\infty S}$ value of 10 km/s is reached for $V_{\infty E}$ values of about 7.6, 6.2, and 3.7 km/s, respectively, for the EV, EM, and EVM trajectories.

Figure 8 shows the speeds at infinity V_∞ relative to Mars and Venus as dashed lines and the periapsis speeds V_P in the atmosphere, again as a function of launch velocity $V_{\infty E}$.

Figure 9 shows the travel times to the first perihelion for a Solar Probe mission as a function of $V_{\infty E}$.

Figure 10 shows the total bending angle and the gravity and aero components at Mars and Venus, as a function of V_∞. The total curves are the bending (gravity + aero) to place the exit perihelion at Venus and either the exit aphelion at Mars for the Sun trajectory or the exit perihelion at Mars for the Pluto trajectory. The curve marked "Venus, aero" is the difference between the total and the gravity only curves, i.e., the aero bending required. The Venus curves are all dashed.

Figure 11 shows the aero lift accelerations at Venus and Mars as a function of V_P. One can see that aero acceleration, which can impact vehicle design, becomes large at high speeds. The limit of present technology to compute heating is about $V_P=15$ km/s, for which the accelerations are about 3 and 6 g, respectively, for Venus and Mars.

Figure 12 shows the AGA atmospheric flight time as a function of $V_{\infty E}$ for the EVM (Earth, Venus AGA, Mars AGA) missions. The Venus data is shown as a dashed line. The Mars data is shown for the two destinations past Mars.

Figure 13 shows the velocity loss due to drag, as a function of V_P for AGA maneuvers at Mars (shown as dashed lines) and Venus, per radian of aero turn angle, with vehicle L/D ratio as a parameter, for L/D values of 9, 7, and 5, from Eq. (5).

Discussion

From Figs. 6–13, one can choose conditions to illustrate some possible missions: 1) a Solar Probe trajectory to four solar radii R_s, using AGA maneuvers at Venus and Mars (EVMS trajectory); and 2) trajectories to Pluto in a time of seven years (EVMP) or five years (EVMP), as shown in Tables 2 and 3. The inclination in degrees, the launch velocity $V_{\infty E}$ in km/s, and the velocity at planetocentric periapsis V_p in km/s are tabulated. For the Pluto trajectories, the travel time in years is also shown.

To check these predictions, which are based on idealized circular coplanar planetary orbits, a computer program (MIDAS)[8] dealing with the real motion of the planets was used to find several actual dates and parameters for these missions. Table 4 shows preliminary results of the use of MIDAS: an EVMS and an EMS trajectory to the Sun in 2007 and 2003, respectively. Table 4 compares the ideal with the actual (MIDAS) mission (both ignore aero drag losses). The difference between the ideal V_∞ and the actual V_∞ is attributable to the fact that the real orbits are neither coplanar nor circular and to adjusting the bend angle to target to the next body. We see that the $4R_s$, $i=90$-deg Solar Probe trajectory requires high speed at Mars (~24 km/s on the average), whereas missions to Pluto can trade speed vs travel time, as shown in Tables 2 and 3.

It is interesting to compare a trajectory to Pluto via Jupiter having the same launch energy as the Solar Probe mission, i.e., having a $V_{\infty J}$ of about 13.1 km/s, that could have its Jupiter flyby changed to place the perihelion of the resulting orbit at Jupiter. It would then have $V_{\infty S}=18.5$ km/s; this level of $V_{\infty S}$ could be achieved in a Mars (EMP) AGA maneuver with a $V_{\infty M}$ of 14.7 km/s and $V_{p,M}$ of 15.5 km/s (Fig. 8), leaving Earth on a EMP trajectory with $V_{\infty E}$ of about 8.25 km/s (Fig. 7). This speed at Mars is almost within present technology. Since the Mars-Pluto geometry will be reasonable for a few months every 23 months (Mars period), and the Jupiter-Pluto geometry will be reasonable for a few years every 12 years (Jupiter period), there will be more frequent opportunities to go to Pluto via Mars than via Jupiter. The total time to Pluto would be about 7 years instead of more than 12 years going via Jupiter with a gravity assist at Jupiter. Of course, one could aim for a higher $V_{\infty M}$ or a shorter time to Pluto at the expense of greater $V_{p,M}$ and higher $V_{\infty E}$.

Aero-Gravity-Assist Drag Losses

The mission design points derived from these data do not include drag loss in the atmosphere, which may be considerable, although in principle it can be offset by excess initial launch speed. For example, the $i=90$ deg, $4R_s$ Solar Probe mission requires about 24 km/s exit from Mars. From Fig. 8, this requires $V_{\infty E}$ of about 6.7 km/s on an EVMS trajectory, with $V_{\infty V}=14.2$, $V_{p,V}=17.5$, and $V_{pM}=24.8$ km/s. From Fig. 10, an aero turn of about 78 deg is required at Venus and about 87 deg at Mars. From Fig. 13, with $L/D=7$ and $V_{p,V}=1.75$, for example, we find $\Delta V_\infty/V_\infty=0.18$ and for $V_{\infty V}=14.2$ and $\Delta\phi=78/57$ rad; $\Delta V_{\infty V}=0.18{*}14.2{*}78/57 \approx 3.5$ km/s. Similarly, for Mars, with $V_{pM}=24.8$, we find $\Delta V_\infty/V_\infty=$ 0.145 and for $V_{\infty M}$ 24 and $\Delta\phi=87/57$ rad; $\Delta V_{\infty M}=0.145{*}24{*}87/57\approx 5.3$ km/s. Looking in Fig. 8 for $V_{\infty V}$ of 17.7 (14.2 + 3.5) and $V_{\infty M}$ of 29.3 (24 + 5.3), we find $V_{\infty E}$ of 8.8 and 8.9, respectively, to offset the losses individually. To offset them both together, one would evidently be required to begin with $V_{\infty E}$ of over 9 km/s.

Again, for a 6.6-year Mars-Pluto mission on an EMP trajectory, from Fig. 1, we have $V_{\infty S}=18.5$ km/s. From Fig. 7, we have $V_{\infty E}=8.3$, and from Fig. 8, we have $V_{\infty M}=14.5$, $V_{p,M}=15.5$ km/s. From Fig. 10, the aero bending angle is about 66 deg, and from Fig. 13, with $L/D=7$, we have $\Delta V_{\infty M}=0.152{*}14.5{*}66/57\approx 2.5$ km/s. From Fig. 8, a $V_{\infty M}$ of 17.0 (14.5 + 2.5) is achieved for $V_{\infty E}=10.3$, i.e., about 2.0 km/s at Earth launch will compensate for the 2.5 km/s or so drag loss in the Mars AGA maneuver.

Aero-Gravity-Assist Technology Issues

A Solar Probe type mission at $i=90$ deg calls for speeds in the atmosphere of Mars somewhat in excess of 24 km/s. At present, it would be difficult to even compute the aero heating rates for this speed in carbon dioxide particularly radiative heating, possibly as modified by ablation. In addition, there are problems with the high aero g loading at this speed and at high temperatures, packaging of the payload to achieve aero stability, achieving high enough L/D to avoid excessive loss of speed due to aero drag, navigation in the entry and exit conditions, and control of altitude in the atmospheric pass. However, our capabilities in some of these areas are expected to improve with the current renewed interest in high hypersonic flight speeds, in high-temperature materials, in computational aerodynamics, in navigation and path control for aerocapture type maneuvers, in highspeed aircraft and flight experiments, and experience on other missions. In a recent paper,[9] results of detailed simulations at the University of Maryland suggest waverider stagnation point temperatures >10,000 K at $V_{p,V} \approx 20$ km/s, compared with the temperature of 11,000 K for the Galileo atmosphere probe.

In the shorter time scale, a mission to Pluto via Mars may be a more reasonable objective, with a choice of Earth launch energy, atmospheric speed at Mars, and travel time to Pluto that is a reasonable compromise for a modified waverider high-lift vehicle in which the heating rates, guidance, and control are close to present technology.

Conclusions

Mars is a better candidate than Venus or Earth for aero-gravity-assist maneuvers because the speeds in the atmosphere are considerably less. For example, a polar trajectory Solar Probe mission with perihelion at $4R_s$ requires an exit speed of about 25 km/s (average, range is about 23–27) at Mars, compared with 32 at Earth and 37 at Venus. At these speeds, the aero lift loading is about 18, 16, and 22 g for Mars, Earth, and Venus, respectively. A vehicle with a coefficient m/C_LA of 50 kg/m^2 would fly at about an altitude of 60 km at Mars. A somewhat lower speed at Mars is needed for a Solar Probe type mission at greater perihelion distance or in the ecliptic ($i=0$), as distinct from polar. The speeds for the Solar Probe mission are considerably beyond present technology.

On the other hand, a mission to Pluto is flexible in that one can trade speed at Mars for trip time to Pluto, and it is likely that with present technology one can design a high-lift vehicle flying an aero-gravity-assist maneuver at Mars that would improve on the trip time of about 15 years associated with present conventional mission studies.

It is found that a given mission calls for much less Earth launch energy if the aeromaneuver is performed in two steps, e.g., a maneuver at Venus prior to the maneuver at Mars. In this case, the speed at Mars is essentially unchanged, and the speed at Venus is moderate. However, the aeromaneuver at two planets may impose restrictions on mission opportunities compared with single planet missions.

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