Venus-Swingby Mission Mode and Its Role in the Manned Exploration of Mars

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The present study offers a systematic, thorough analysis of all Venus-swingby opportunities over the extended period of time during which such missions seem most relevant; accurate plots of the speed requirements for these trips; and a critical interpretation of the Venus-swingby mode as it affects the various direct-mode choices previously treated by many analysts. The data are plotted in a manner compatible with the direct flight mission charts presented in the NASA *Planetary Flight Handbook*, SP-35. Generally speaking, swingby mission opportunities are governed by a basic 6.4-yr syzygistic cycle involving Earth, Mars, and Venus. Within each such cycle, three groups of outbound swingby missions and three homebound groups are worthy of consideration. Study reveals that of these six, two groups are never worthwhile, two always favorable, and two occasionally so. Treating the Venus-swingby mode within the totality of possible trajectory types, it is possible to attempt a general philosophy of approach to a long-term Mars exploration program which views this mode in perspective within the total mission spectrum.

Introduction

HOLLISTER[1] and Sohn,[2] in independent and almost simultaneous works, demonstrated that the strong synodic fluctuation in mission requirements for fast round trips to Mars could be greatly reduced by employing close approaches to Venus enroute, causing its mass to favorably modify nominally unacceptable trajectories (Fig. 1). Almost immediately, widespread attention was focused upon the "Venus-swingby mission" (as Sohn called it), and results of subsequent studies by Sohn[3,4] and by Deerwester[5] were soon disclosed. Sohn[3] examined some representative swingby trips applied to nonstop as well as stopover missions over a span of years between 1970 and 1999 and firmly established the feasibility and the desirability of employing this mission mode. Deerwester's treatment[5] embodied two important contributions, the first of which was his exhaustive exploration of two sample swingby opportunities, and the second his method of graphical presentation of the results, which makes them compatible in format with the direct flight curves presented in the NASA *Planetary Flight Handbook*.[7] Using this manner of presentation, it is possible to match homebound swingby trajectories with direct outbound flights, and vice versa, and to then analyze complete missions on a common graphical basis. Deerwester's study also encompassed representative missions from other launch-year opportunities, confirming Sohn's and Hollister's earlier statements that the Venus-swingby trips would often require considerably less initial mass than equivalent direct trips—especially so in many of the "unfavorable years," when the Martian orbital eccentricity makes short, direct flights prohibitive by raising terminal speeds beyond reasonable limits. The swingby trips generally involve only modest terminal speeds, they are not unduly long in duration, and their navigational requirements are no more severe than what in any event would be required to return a crew capsule to Earth at the end of any Mars mission.

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Now, possibilities for employing the Venus-swingby mission mode are bound up quite intimately with the orbital geometry of the three planets involved. The eccentricity of Mars' orbit leads to significant variations in trajectory requirements, further complicating the physical problem and preventing any sort of serious attempt to formulate a generalized precise theory of such missions. Thus, although studies of specific groups of trajectories, such as the ones mentioned previously, can serve to demonstrate the feasibility of such flights, it still remains for a comprehensive, detailed study of the entire time span of interest to produce the quantitative data necessary to locate all trajectories that might be profitably exploited. With this in mind, we investigated and cataloged all useful swingby trajectories, both outbound and homebound, during a period (1981–1987) within which these flights might be usefully employed.

Geometrical and Temporal Properties

A remarkable commensurability among the orbital periods of Earth, Venus, and Mars causes relative configurations among the three bodies to repeat fairly closely every (approximately) 2338 days, which constitutes a syzygistic period for these planets. Five syzygistic periods constitute a syzygistic cycle of (almost precisely) 32 years, at the end of which time the three planets occupy the same absolute positions in space as they did at the start.

August 24, 1987 (JD 244 7032) is an interesting date of symmetry on which the three planets and the sun lie on a straight line,‡ rotated only 4 deg from the line of apsides of Mars' orbit. It is easy to show then[6] that each swingby trajectory involving a series of dates $D_1, D_2, \ldots, D_n$ relative to JD 244 7032 corresponds to a geometrically identical trajectory, traveled in the opposite direction, involving dates $-D_n, \ldots, -D_2, -D_1$; departure speeds at any point in the former case correspond to approach speeds at that point in the latter case, and vice versa.

Within any syzygistic period, alignments between Mars and Venus repeat seven times, and are the most frequently recurring planetary phenomenon. Therefore, seven opportunities§ exist within every syzygistic period for scheduling,

‡ Assuming, for the moment, that the planetary orbits are coplanar.

§ Actually, seven in each direction: outbound and homebound.

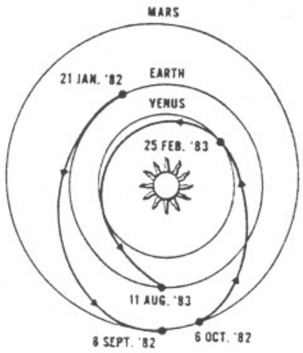

Fig. 1 Homebound Type 3 Venus swingby, 1983.

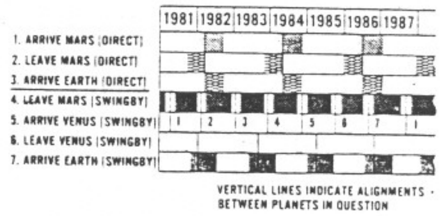

Fig. 2 The syzygistic timing cycle for homebound Venus swingbys.

between Mars and Venus, "easy" mission segments whose energy requirements are relatively modest and whose flight durations are relatively brief. The question is, how many of these seven groups can be successfully mated with other segments to form useful total missions? Figure 2 addresses this question and helps to qualitatively determine the relative merit of each mission opportunity.

For practical reasons, individual trajectory segments between each pair of planets should be short in duration and must involve only modest speeds at Earth and Mars, where injection and capture maneuvers are to be performed. Previous analyses (e.g., Ref. 7) have established that such favorable segments between each pair of planets leave and arrive well within the time intervals denoted by the appropriate shaded bands in Fig. 2. Numbers within the shaded bands in Row 5 identify the seven basic groups of flights from Mars to Venus. Mission Types 2, 4, and 6 are immediately eliminated from further consideration since no trajectories exist which leave Venus for Earth when these three groups arrive at Venus from Mars (Rows 5 and 6). Mission Type 7 is theoretically possible but not actually competitive with the direct homebound flights that leave Mars during the same time period but arrive at Earth substantially earlier (Rows 2 and 3).

Mission Types 1, 3, and 5 remain to be considered. The shaded areas in Rows 5 and 6 which correspond to Type 1 missions overlap only narrowly. Furthermore, the wide gap between regions in Rows 1 and 5 which apply to Type 1 trips indicates that long stopover times at Mars and long total trip times are to be expected; consequently we expect this group to be only marginally useful. At Venus, Type 3 trajectories enjoy good temporal overlap with segments passing from Venus to Earth (Rows 5 and 6) and thus appear to be highly promising. Type 5 trajectories also enjoy good temporal overlap at Venus. However, they may suffer timing incompatibilities at Mars, since direct outbound flights from Earth sometimes arrive at Mars after the corresponding homebound swingby trips are to have left Mars for Venus (Rows 1 and 4). The eccentricity of Mars' orbit causes this condition to vary in severity, and each opportunity must therefore be examined separately to determine its suitability. On occasions when such timing incompatibilities are found to exist at Mars, it is possible to employ Type 5 Venus-swingby trajectories on both outbound and homebound flights and, at the price of increased total trip time, to use the gravitational effect of Venus to create acceptable stopover windows at Mars.

In summary then, trajectory Types 2, 4, and 6 appear unfeasible, Type 7 is not competitive with direct flights, Type 1 seems doubtful, Type 5 is of occasional interest, and Type 3 promising. By the symmetry principle quoted earlier, these considerations apply to outbound, as well as homebound, Venus-swingby missions.

Numerical Investigations

Based on the qualitative arguments offered herein all indicated opportunities within a 6.4-yr syzygistic period beginning in 1981 were analyzed using fine-grid search techniques and a digital computer program to generate acceptable trajectories. Valid missions exist only for those trajectories whose hyperbolic speeds of arrival and departure at Venus coincide, and whose asymptote bend angles at Venus are properly offset. Matching these conditions produces, for each opportunity, small mission areas centered about the points labelled "Type 5 Swingby" or "Type 1 Swingby" in Figs. 3 and 4, for which the appropriate speeds of departure and arrival are labeled as shown (i.e., for Type 5 swingby in Fig. 5: 0.25 EMOS departure from Earth and 0.26 EMOS arrival at Mars, and so on). These points are not meant to represent "optimum" missions in any definite sense, but rather to serve as handy indicators for locating and assessing favorable working areas for detailed study. Figures 3 and 4 display all such useful working points obtained for the 6.4-yr period under study. These are presented in proper temporal relationship to the direct flight curves with which they are to be matched and compared. As Fig. 5 shows, no usable engineering regions were found for the Type 1 swingby missions occurring in 1981, although detailed data for this opportunity are presented in Fig. 6, below.

Important properties of selected total missions that involve these points are summarized in Table 1. In practice, most useful missions will not differ appreciably from the examples outlined there.

Figure 7 shows the complete mission areas corresponding to outbound and homebound Type 5 swingbys in 1984. Type 5 missions can be used either separately or together as follows: outbound swingby, homebound direct; outbound direct, homebound swingby; outbound swingby, homebound swingby. Figures 6 and 8–12 display, in expanded scale, the detailed contours that describe each complete mission area throughout the syzygistic period, plotted following the

Table 1 Selected Venus-swingby trips between Earth and Mars during a single syzygistic cycle of 6.4 years

Type	Syzygy date	Total trip time, days	Stopover time, days	Terminal speeds in EMOS			
				LV	AR	LV	AR
1 Homebound	Apr. 5, 1981			(No engineering window)			
3 Homebound	Jan. 31, 1983	567	28	0.15	0.11	0.21	0.17
5 Outbound	Dec. 24, 1983	446	20	0.25	0.26	0.15	0.30
5 Homebound	Nov. 27, 1984	464	18	0.14	0.30	0.18	0.13
3 Outbound	Oct. 23, 1985	560	29	0.14	0.20	0.11	0.11
1 Outbound	Aug. 24, 1987			(No engineering window)			

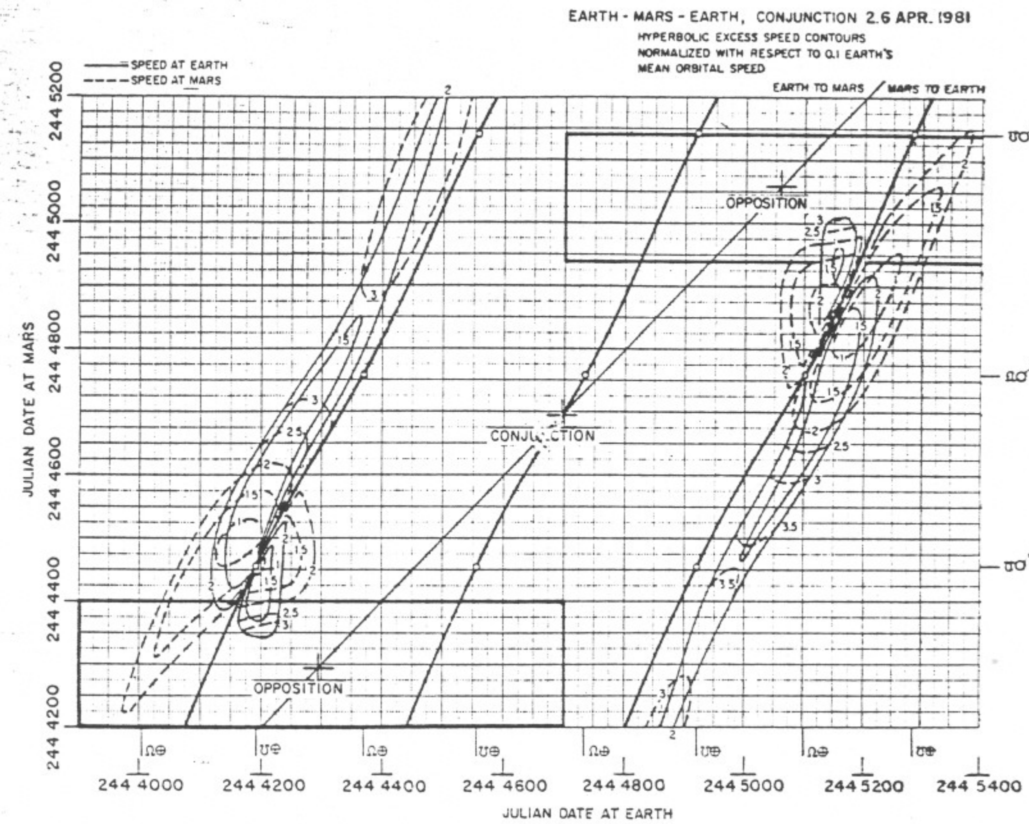

Fig. 3 Selected trips: homebound Venus swingby, Type 3, 1983, and outbound Venus swingby, Type 5, 1983.

method adopted by Deerwester.[5] From each figure the following quantities can be read for all missions: departure date [ordinate (or abscissa)], arrival date [abscissa (or ordinate)], passage date (thin solid contours), passage height at Venus (thin dashed contours), hyperbolic excess speed at Mars (heavy dashed contours), and hyperbolic excess speed at Earth (heavy solid contours).

Study Results

The study confirmed that no mission opportunities of Types 2, 4, and 6 exist, either outbound or homebound. In addition, no Type 1 missions were found to be of practical interest; high terminal speeds and, in many cases, requirements for subsurface Venusian passages reflect the effects of the tight

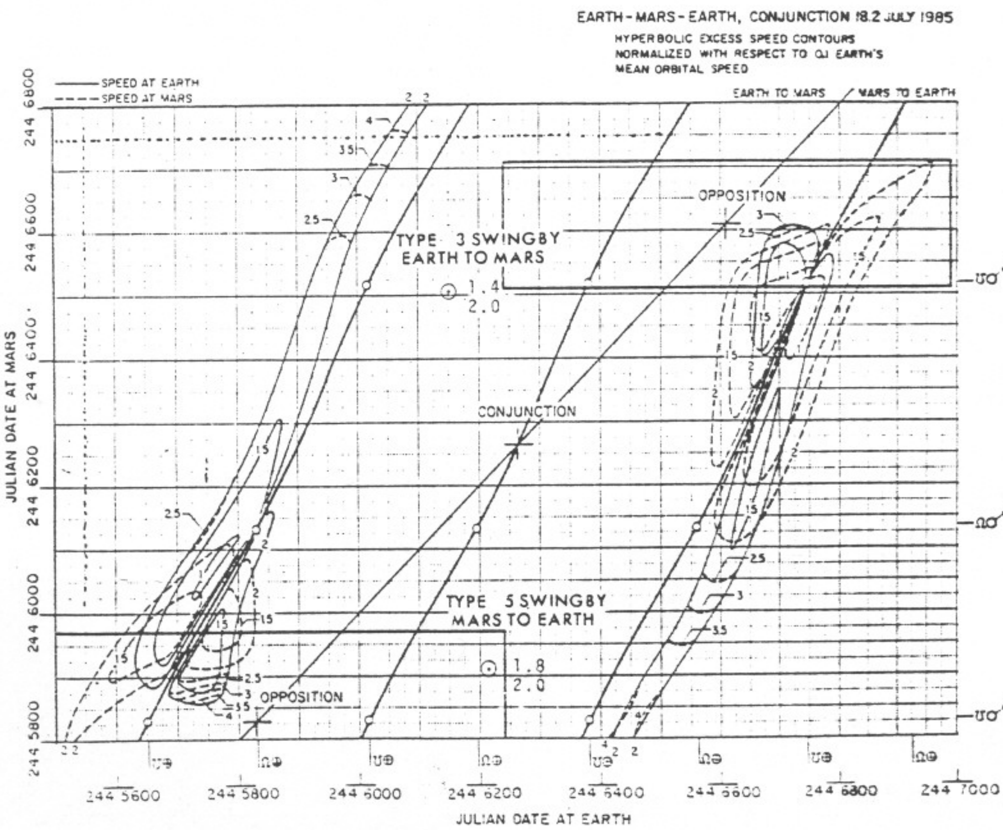

Fig. 4 Selected trips: homebound Venus swingby, Type 5, 1984, and outbound Venus swingby, Type 3, 1985.

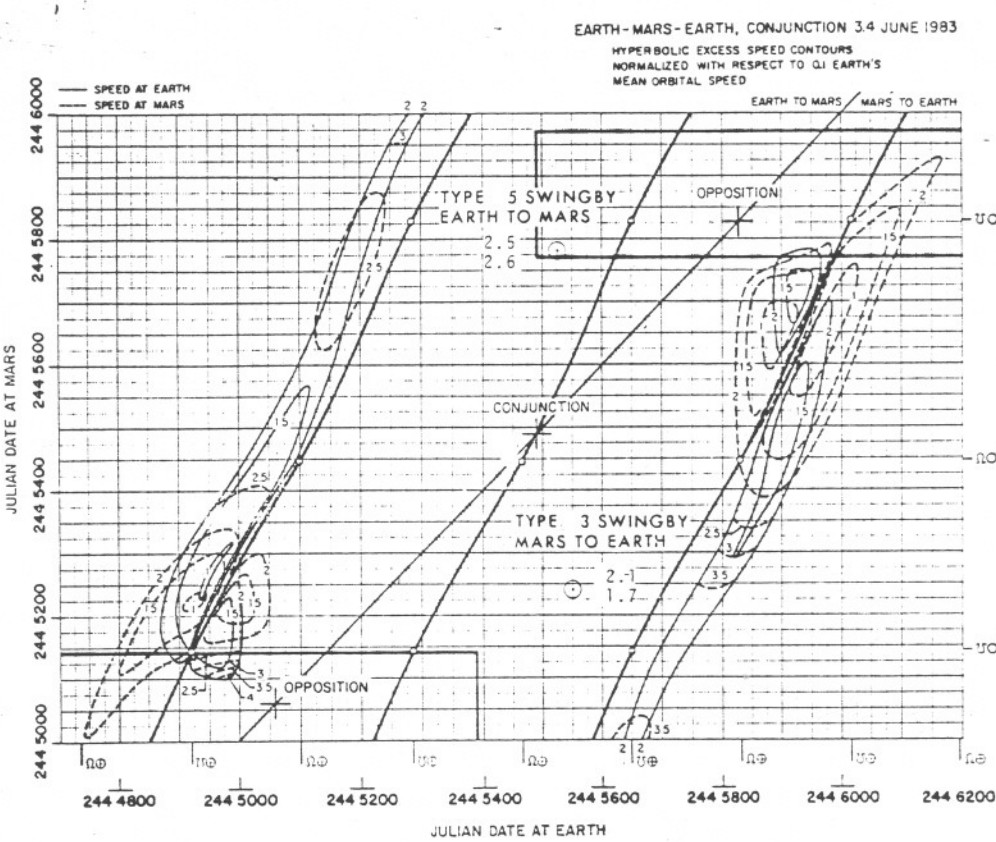

Fig. 5 Contour charts for 1981 showing no usable swingby trips.

timing conditions during passage which were mentioned earlier. A minor exception occurs, however, during the outbound opportunity of 1974 (not treated here), during which a very small area of barely possible interest exists, with hyperbolic excess speeds of 0.26 EMOS (minimum) at both Earth and Mars. This area repeats once during each 32-yr syzygistic cycle.

All Type 3 swingby missions, both outbound and homebound, were found to be highly advantageous. Terminal speeds are low and trip durations are almost invariant at about 550 days, including stopovers of 0–30 days, typically. The nominal interval between Type 3 swingbys, alternately outbound and homebound, is 3.2 years, regularly and for decades into the future.

Type 5 swingby trips occur in pairs, outbound and homebound, about every 6.4 years. Instead of arriving at Mars near the date of conjunction, as in the case of Type 3 trajectories, they arrive near the date of opposition. Also, as distinguished from the Type 3 trips, they can be used separately or together, as previously mentioned. Terminal speeds and stopover durations are not appreciably different from those for Type 3 trips. However, round-trip durations are typically about 460 days, instead of the 550 days involved in Type 3 missions.

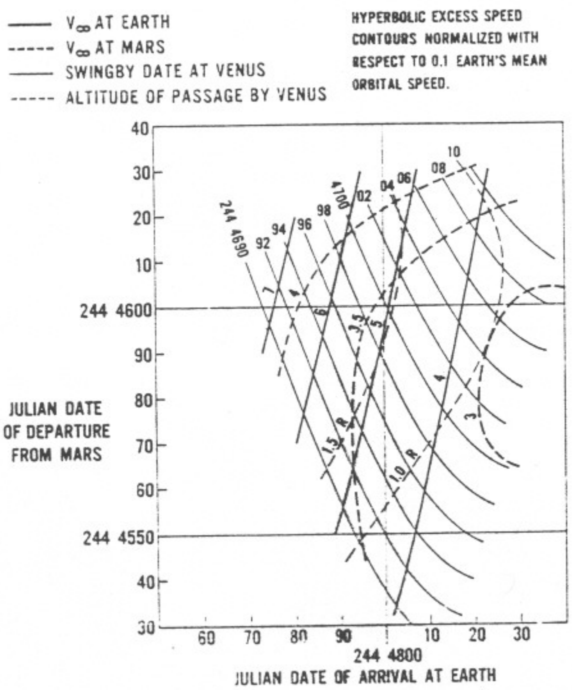

Fig. 6 Homebound Type 1 Venus swingby; syzygistic event of April 5, 1981, JD 244 4700.1.

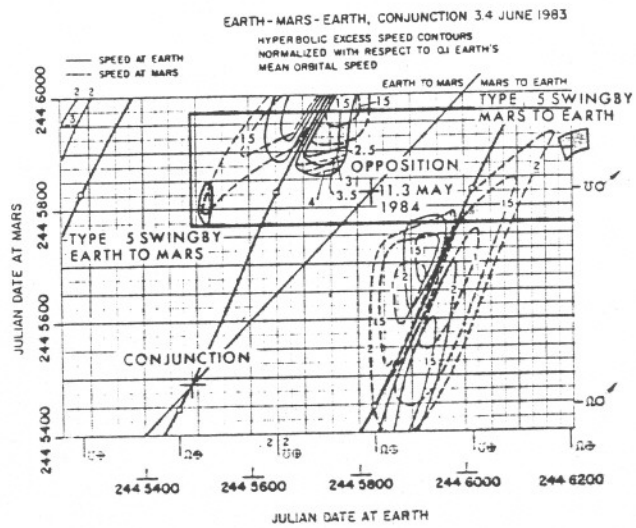

Fig. 7 Trip windows, direct and Type 5 Venus swingby, 1983.

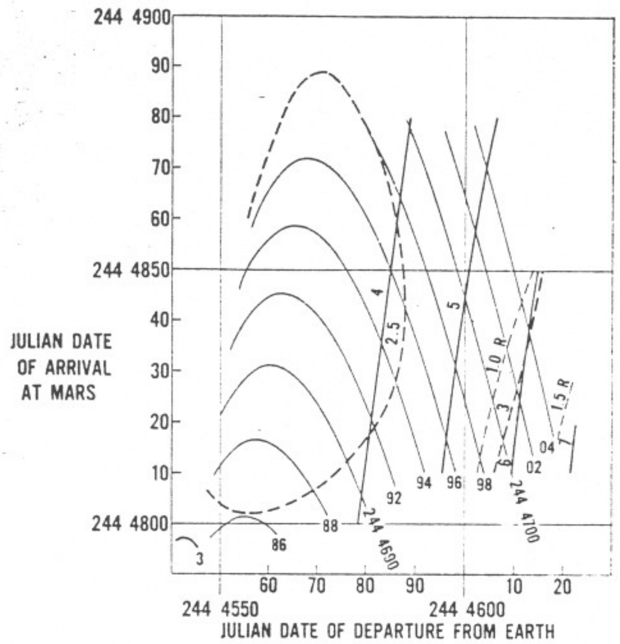

Fig. 8 Outbound Type 1 Venus swingby; syzygistic event of April 5, 1981, JD 244 4700.1.

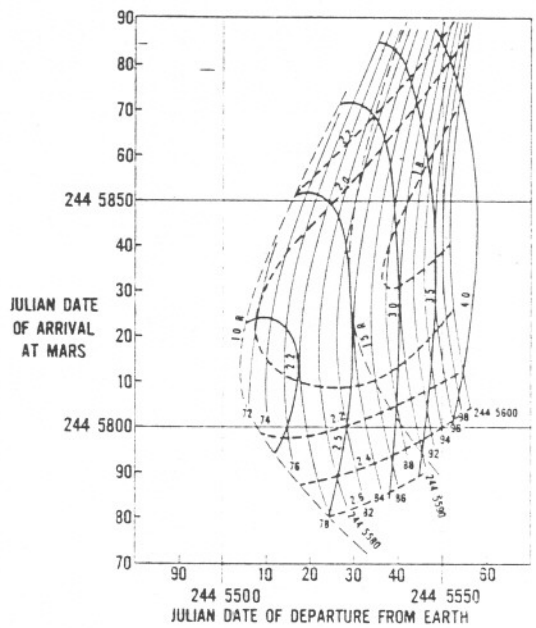

Fig. 10 Outbound Type 5 Venus swingby; syzygistic event of Dec. 24, 1983, JD 244 5693.0.

A Comprehensive Assessment

Sufficient information now exists to make a valid and general engineering comparison of Venus-swingby missions with direct missions to and from Mars. The direct trips fall into two groups, opposition-class trips and conjunction-class trips.

Opposition-class trips are each characterized by a brief stopover opportunity at or near the date of opposition every synodic period of (nominally) 2.13 years. Owing to the eccentricity of the orbit of Mars, the round-trip time varies from typically 400 days at Martian "perihelion oppositions" to 500 days at Martian "aphelion oppositions," each of these extremes repeating every 15 or 17 years. Perihelion oppositions permit stopover durations of perhaps 20–50 days. Other oppositions permit stopovers of only a few days' duration. Terminal speeds, in terms of either chemical or solid-core nuclear propulsion, range from difficult in perihelion oppositions to impossible in others.

Conjunction-class trips are characterized by long stopover opportunities centered at the date of conjunction; these also occur every 2.13 years. All are uniformly alike throughout the entire synodic cycle of 15 or 17 years, so that if a capability for one is engineered, all are automatically included. Conjunction-class trips can be varied between two extremes, from the classical double-Hohmann trip of about 900 days, having a 550-day stopover at Mars, to a zero-stopover trip of about 800 days. All intermediate combinations are possible. The 800-day trip requires terminal speeds just comfortably within the capability of the chemical propellants and present engineering knowledge. They are the most difficult of the conjunction-class trips; double-Hohmann missions are the easiest, as far as propulsion is concerned.

Type 3 and Type 5 Venus-swingby trips both require approximately the same propulsion capability as the 800-day

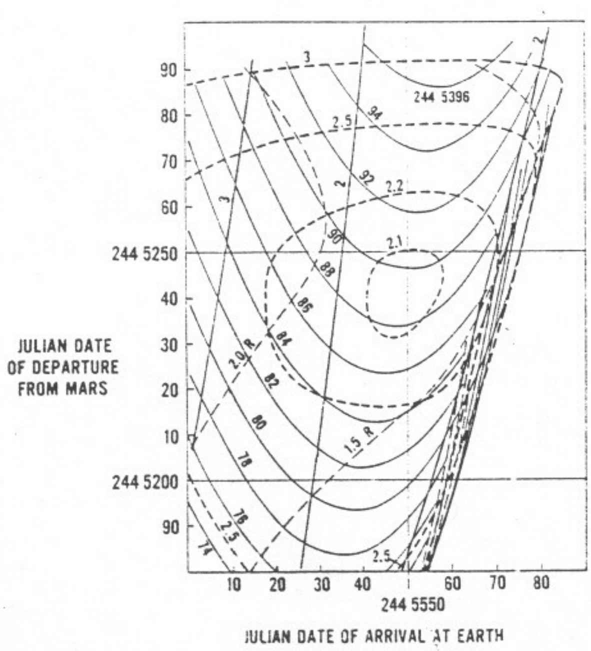

Fig. 9 Homebound Type 3 Venus swingby; syzygistic event of Jan. 31, 1983, JD 244 5366.0.

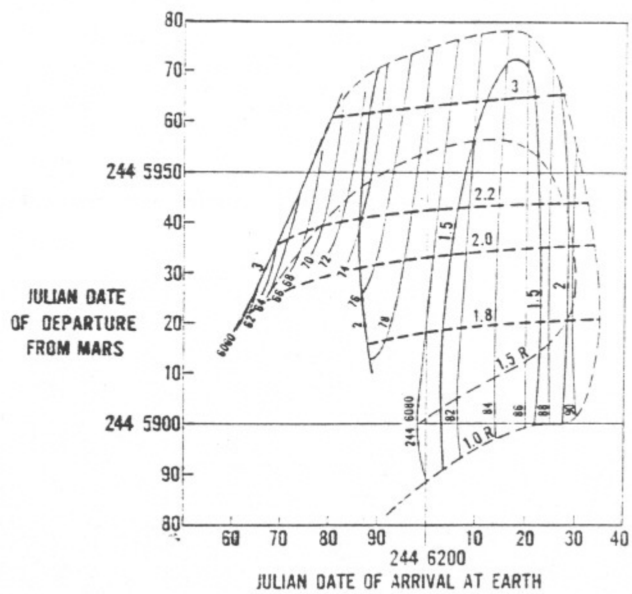

Fig. 11 Homebound Type 5 Venus swingby; syzygistic event of Nov. 27, 1984, JD 244 6031.7.

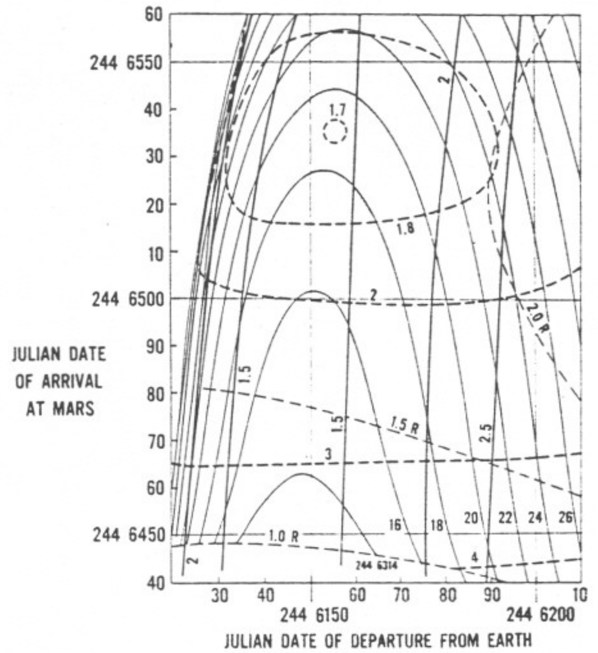

Fig. 12 Outbound Type 3 Venus swingby; syzygistic event of Oct. 23, 1985, JD 244 6362.3.

conjunction-class trips. Type 3 trip opportunities occur alternately every 3.2 years. Type 5 trip opportunities occur in pairs every 6.4 years. The same capability can be used to include both conjunction-class trips and Venus-swingby trips. It therefore seems clear that no choice should be made between direct trips and Venus-swingby trips, but that a repetitive capability can be established, leaving to future decisions the selection of modes for each individual expedition. An occasional opportunity to make an opposition-class trip, say in 1971, 1988, etc., could be utilized by using fleets of rockets designed for the conjunction-class and Venus swingby trips.

A final comment is pertinent. Such preliminary engineering evaluations as have been made indicate that Venus-capture expeditions can be accomplished with approximately the same propulsion capability as is required for Mars conjunction-class and Venus swingby landings.

Once the syzygistic period has been completely described, the results can then be used as a guide in computing trajectories during subsequent periods. However, since the heliocentric longitudes of the planets at any time within the 6.4-yr interval are different in successive periods, and since the orbit of Mars is relatively eccentric, the events in one period are not exactly reproduced during the period following. Thus, although the pattern set by any period guides us in calculating the events in the following cycle, it does not eliminate the need for complete and detailed calculations for each opportunity of interest. A compilation of contour maps and tabulation of supporting calculations for the entire period from 1975–2000 is now in preparation and will be issued shortly in a new volume as part of the *Planetary Flight Handbook Series*.[7]

References

[1] Hollister, W. M., "The mission for a manned expedition to Mars," Sc.D. Thesis, Massachusetts Institute of Technology, Cambridge, Mass. (1963).

[2] Sohn, R. L., "Summary of manned Mars mission study," *Proceedings of the Symposium on Manned Planetary Missions, 1963/1964 Status*, NASA TM-53049, Pt. 5 (June 12, 1964).

[3] Sohn, R. L., "Venus swingby mode for manned Mars missions," J. Spacecraft Rockets **1**, 565–567 (1964).

[4] Sohn, R. L., "Manned trips using Venus flyby modes," J. Spacecraft Rockets **3**, 161–169 (1966).

[5] Deerwester, J. M., "Initial mass savings associated with the Venus swingby mode of Mars round trips," AIAA Paper 65–89 (1965).

[6] Ross, S., "A systematic approach to the study of nonstop interplanetary round trips," Advan. Astronaut. Sci. **13** (1963).

[7] Ross, S. (ed.), *Space Flight Handbooks, Vol. 3—Planetary Flight Handbook*, NASA SP-35 (1963).