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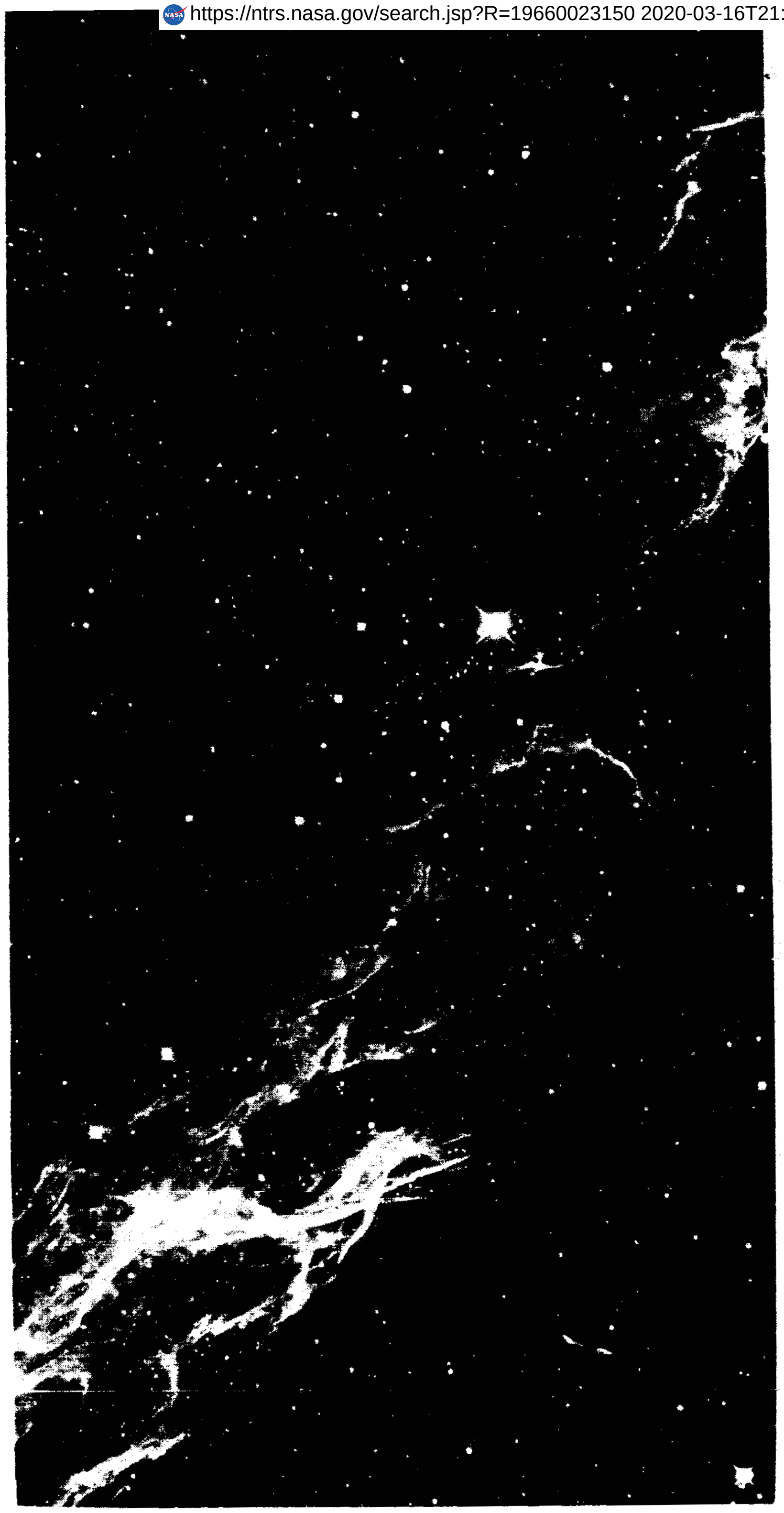

Report No. M-12

A SURVEY OF MULTIPLE MISSIONS USING GRAVITY-ASSISTED TRAJECTORIES

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A SURVEY OF MULTIPLE MISSIONS USING GRAVITY-ASSISTED TRAJECTORIES

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SUMMARY

Over the past several years a number of general studies have been performed to investigate the advantages of gravity-assisted trajectories in solar system exploration. Results of these studies continue to indicate some significant improvements over direct trajectories. Very few studies, however, have been concerned with the practical application of gravity assist to specific missions.

Thus the objectives of this survey were to briefly analyze gravity-assisted multiple missions to a number of specific solar system targets and to recommend for further analysis those missions that have practical advantages over direct missions to the same targets. The scope of the survey included Venus-assisted missions to Mercury, several outer-planet gravity-assisted missions, out-of-the-ecliptic missions, solar probes, reconnaissance (Earth return) missions, gravity assist to the asteroids (as a group and individually), and comet rendezvous missions. In addition, satellite gravity assist for orbital maneuvers was assessed.

Six recommended multiple missions are reviewed in the summary table. The Earth-Venus-Mercury mission has already

SUMMARY OF MULTIPLE MISSIONS RECOMMENDED FOR FURTHER STUDY

Mission	Launch Opportunities	Principal Objectives	Advantages over a Direct Mission	Ideal Velocity, ft/sec	Trip Time
Earth-Venus-Mercury	1970 and 1973	Surface temperature and magnetic field measurement, atmosphere investigation (by occultation and Venus drop sonde), and mass determinations.	Improved payload and multiple objectives	43,000	175^{d}
Earth-Jupiter-Saturn-Uranus-Neptune	1977 or 1978	Combined investigation of all outer-planet (except Pluto) atmospheres and magnetic fields.	Better spacecraft utilization and reduced flight time to Neptune	55,000	8.6^{y}
Earth-Jupiter-90° Out-of-the-Ecliptic	Once every 13 months	Investigation of interplanetary medium at all solar latitudes (solar probe or Earth recovery objectives may be added).	Significantly reduced energy requirements	56,000	$3.5\text{-}4.0^{y}$
Earth-Venus (single or multiple)-solar probe	Once every 19 months	Investigation of solar corona to 0.1 AU combined with Venus flyby objectives. Also, solar surface astronomy at extremely low scan rates.	Improved perihelion reduction and multiple objectives	$<65,000$	$<2.0^{y}$
Earth-Jupiter-solar probe	Once every 13 months	Investigation of solar corona between 0.1 AU and apparent solar surface.	Significantly reduced energy requirements	56,000	2.5^{y}
Earth-Mars-asteroid fly-through	Once every 26 months	Deep space flight test (including gravity assist) of precursor spacecraft to outer planets and assessment of asteroid hazards.	Increased asteroid belt penetration and inclusion of a gravity-assist maneuver	$<46,500$	$<3.0^{y}$

received some attention (Cutting and Sturms 1964). Recent trajectory studies (Sturms 1966) indicate, however, that only two good opportunities (1970 and 1973) for such a mission exist between now and 1981. Further study is recommended to determine the constraints imposed by this mission on a Venus flyby in 1970 or 1973, especially if Venus drop sondes for atmospheric experiments are planned.

Detailed gravity-assist outer-planet mission studies are needed soon. Advanced planning of planetary exploration indicates that the first extensive use of gravity-assisted trajectories will be made for these missions. Study of the Earth-Jupiter-Saturn-Uranus-Neptune "Grand Tour" (Flandro 1966) is recommended since it typifies these missions.

Moderate-energy, 90° out-of-the-ecliptic missions with a Jupiter assist will provide interplanetary data at all solar latitudes. A study of the practical value of this mission is recommended as a secondary objective to early Jupiter flybys. Additional objectives for similar follow-on missions should also be evaluated.

Solar probes down to 0.1 AU using single or multiple Venus assists combine a number of useful objectives into one mission. For further reductions in perihelia, Jupiter assists are recommended. Mission studies should focus on spacecraft design problems due to large environment variations between 5 AU and the solar surface.

Finally, as a precursor mission to outer-planet exploration, a Mars-assisted asteroid fly-through is recommended. Attention to development time and the practicality of such a test flight are needed.

In addition to the specific areas of analysis suggested for each of these missions general problems concerning spacecraft design constraints, encounter profiles, guidance and control requirements, and launch window definition should be considered. Two multiple missions are not suggested for further consideration at this time: rendezvous missions (low hyperbolic approach velocities, VHP) to individual asteroids or to the comets in which Mars or Jupiter gravity assist is used. Instead, further analysis of non-minimum energy direct trajectories with minimized VHPs is needed. Some brief considerations of gravity assist for rendezvous are, however, presented.

TABLE OF CONTENTS

		Page
1.	INTRODUCTION	1
2.	EARTH-VENUS-MERCURY MISSIONS	2
3.	OUTER PLANET MISSIONS	8
4.	OUT-OF-THE-ECLIPTIC MISSIONS	24
5.	SOLAR PROBES	31
6.	RECONNAISSANCE MISSIONS	36
7.	ASTEROID MISSIONS	41
8.	COMET RENDEZVOUS MISSIONS	46
9.	PLANETARY SATELLITES	50
10.	CONCLUSIONS AND RECOMMENDATIONS	51
REFERENCES		55

LIST OF FIGURES

		Page
2.1	Ideal Velocity Comparison: Mercury (0.47 AU)	4
2.2	Earth/Venus/Mercury Trajectory Illustration	7
3.1	Spacecraft Weight Bar Chart for Saturn Missions	13
3.2	Spacecraft Weight Bar Chart for Uranus Missions	16
3.3	Spacecraft Weight Bar Chart for Neptune Missions	20
4.1	Out-of-Ecliptic Energy Requirements	25
4.2	Distance Above the Sun for Jupiter-Assisted 90° Orbits	27
4.3	Earth-Jupiter-90°/5.2 AU Orbit Illustration	29
5.1	Jupiter-Assisted Solar Probe Performance	32
5.2	Solar Probe Energy Requirements	35
6.1	Earth-Jupiter-Earth Trajectory Illustration	38
6.2	Jupiter Flyby Illustration (reconnaissance mission)	40
7.1	Distribution of 1500 Numbered Asteroids in B and R on 3/20/73	42
7.2	Asteroid Belt Penetration	43

LIST OF TABLES

		Page
2.1	Some Important Parameters of Earth-Venus-Mercury Launch Opportunities	6
3.1	Synodic Periods Between Outer Planets Considered as Multiple Mission Targets	10
3.2	Suggested Spacecraft/Launch Vehicle Examples for Performance Analysis of Outer Planet Multiple Missions	11
3.3	Flight Times for Saturn Missions	14
3.4	Flight Times for Uranus Missions	17
3.5	Flight Times for Neptune Missions	21
3.6	Periods of Yearly Launch Opportunities for Selected Gravity Assisted Outer Planet Missions	23
4.1	Launch Data for Earth-Jupiter-90°/OOE Missions	30
6.1	Some Important Properties of Terrestrial Planet Reconnaissance Missions	37
7.1	Multiple Asteroid Mission Summary	47
9.1	Comparison of Gravity Assisted Energy Change of Planets and Satellites	52

Report No. M-12

A SURVEY OF MULTIPLE MISSIONS USING GRAVITY-ASSISTED TRAJECTORIES

1. INTRODUCTION

The objective of this survey was to briefly analyze multiple missions to a number of solar system targets and to suggest for further consideration the gravity-assist missions that would be more advantageous than direct missions to the same target.

Gravity assist is a significant trajectory perturbation between launch and the final target due to a close approach (usually less than 25 planet radii) of an intermediate planet. A preliminary analysis of two-dimensional gravity-assisted trajectories can be found in ASC/IITRI Report No. T-12, "An Analysis of Gravity Assisted Trajectories in the Ecliptic Plane".

Advantages of multiple missions include shorter trip times, lower energy requirements, lower approach velocities, and the combining of scientifically similar targets into one mission. However, certain disadvantages are also encountered: stringent guidance requirements, restricted launch opportunities, and trade-offs rather than simultaneous reductions in trip time, energy, and approach velocity. Both advantages and disadvantages of a multiple mission were considered before it was suggested for further study as a useful alternative to a direct mission. A guidance analysis, however, was beyond the scope of this survey.

Multiple missions to the following targets were analyzed:

(1) Mercury
(2) Outer planets (Saturn and beyond)
(3) Out-of-the-ecliptic regions
(4) Solar probes
(5) Reconnaissance (Earth return)
(6) Asteroids (as a group and individually)
(7) Comet rendezvous
(8) Planetary satellites.

In this respect each target is discussed in a separate section, and individual results are collected in the last section in which suggestions for further multiple-mission analyses are made. Note that gravity-assisted and direct trajectories were restricted to ballistic flight; low-thrust flight and impulse augmentation during assist were not analyzed in this survey.

2. EARTH-VENUS-MERCURY MISSIONS

The use of gravity assist from Venus can greatly improve the payload capability of missions to Mercury.

Figure 2.1, a plot of ideal velocity* versus trip time for direct and Venus-assisted trajectories, shows that an absolute minimum-energy mission to Mercury (intercept in the ecliptic plane at 0.47 AU from the Sun) requires an ideal velocity of 45,200 ft/sec and 115 days flight time. A Venus-assist reduces the energy requirement to 43,500 ft/sec with the same flight time. For an Atlas-Centaur launch vehicle this reduction represents an increase in payload from 450 to 1050 lb.

The primary objectives of an early Mercury flyby mission include measurements of its surface temperature, magnetic field, and surrounding environment; optical determination of its geometrical figure; observation of its predominant surface features; investigation of its tenuous atmosphere (by occultation); and refinement of its mass from post-flyby orbit determination. If a Mercury flyby were planned in conjunction with a Venus flyby mission (implying Venus gravity assist), these objectives would be compatible with measurements of the magnetic fields, surface temperature, and mass of Venus. Although a radio occultation experiment could supply information on both planet atmospheres, a separate drop sonde experiment into the Venusian atmosphere

---

* Ideal velocity is the ideal launch vehicle velocity required (in ft/sec) to achieve a given hyperbolic excess velocity (VHL) beyond Earth escape from a 100 NM parking orbit, assuming all losses from launch to escape are equivalent to 4000 ft/sec. The equation for ideal velocity is

$$\Delta V = \left[(36,178)^2 + (VHL)^2 \right]^{1/2} + 4000 \text{ ft/sec} .$$

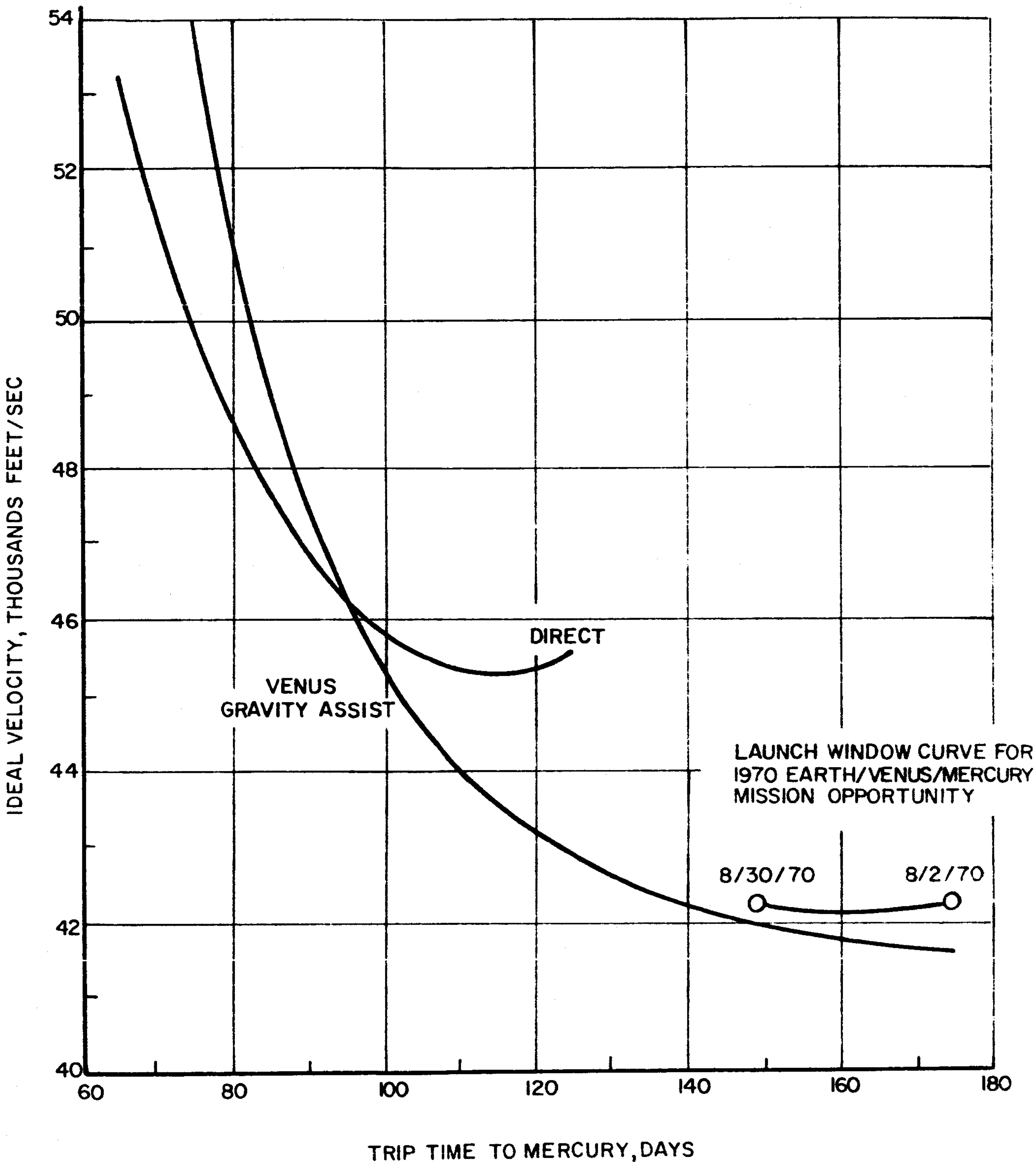


FIGURE 2.1. IDEAL VELOCITY COMPARISON: MERCURY (0.47 AU)

could also be incorporated into the double planet flyby mission profile.

A list of 30-day launch windows for Earth-Venus-Mercury missions between 1967 and 1973 and certain associated trajectory properties are given in Table 2.1. Each opportunity coincides with a direct Venus opportunity. Because the relative planet positions change from one launch window to the next, some of the trajectory properties shown undergo significant variations. The most apparent changes appear in the miss distance* at Venus and in the trip time. Half the opportunities require minimum miss distances of 200 km or less. The trip times vary from 165 days to almost 300 days.

The most favorable launch opportunity listed in the table occurs in August 1970. It has (1) the largest minimum miss distance requirement, (2) a trip time of 175 days, and (3) a payload of 1650 lb with the Atlas-Centaur. Figure 2.2 is a polar plot of a trajectory from this opportunity. This particular trajectory requires an ideal velocity of less than 42,000 ft/sec, and the trip time is 160 days. The hyperbolic approach velocity (VHP) at Venus is 7.6 km/sec, only about 1 km/sec faster than VHPs for direct Venus missions. Notice in Figure 2.2 that Mercury is near maximum western elongation during intercept. This configuration reduces the noise temperature contribution of the Sun to spacecraft communications,

* Unless otherwise stated, miss distance is measured from the optical surface (this includes atmosphere) of the planet.

Table 2.1

SOME IMPORTANT PARAMETERS*
OF EARTH-VENUS-MERCURY LAUNCH OPPORTUNITIES

Mission Parameters	Launch Windows				
	June 3-July 5, 1967	Jan.5-Feb.2, 1969	Aug.2-Aug.30, 1970	Mar.24-Apr.21, 1972	Oct.21-Nov.16, 1973
Maximum ideal velocity, ft/sec	43,000	43,420	42,110	42,870	42,940
Atlas-Centaur payload, lb	1,260	1,090	1,650	1,300	1,280
Minimum Venus miss distance, km	40	25	2,600	200	2,400
Maximum trip time, days	182	287	175	287	165
Maximum Mercury approach velocity, km/sec	9.6	9.7	12.5	15.6	11.4

*Trajectory data by Minovitch (1963). It should be noted that this data pertains to launch windows and does not, in general, imply matched values of any particular trajectory.

TRAJECTORY DATA:

LAUNCH DATE - AUGUST 1970
IDEAL VELOCITY = 41,950 FEET/SEC
TIME TO VENUS = 100 DAYS
VENUS APPROACH VELOCITY = 7.1 KM/SEC
VENUS CLOSEST APPROACH = 4000 KM
TOTAL TRIP TIME = 160 DAYS
MERCURY APPROACH VELOCITY = 9.2 KM/SEC
MAXIMUM COMMUNICATION DISTANCE = 1.15 AU

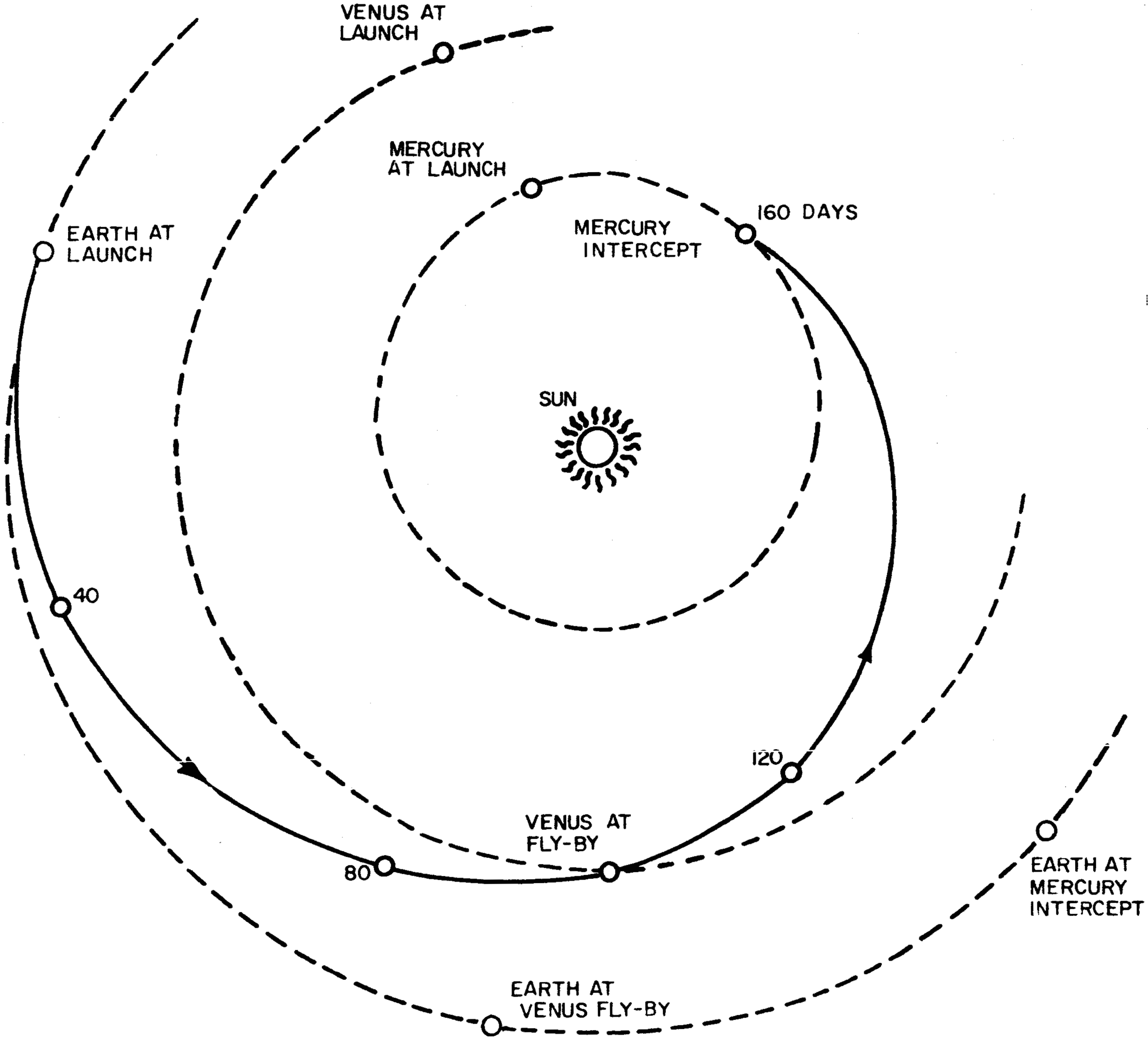


FIGURE 2.2. EARTH/VENUS/MERCURY TRAJECTORY ILLUSTRATION

a critical factor to be considered if the radio occultation experiment is desired. The total guidance requirements for the 1970 opportunity have been shown to be modest (Cutting and Sturms 1964). A 1650 lb payload would require only about 185 lb for propulsion hardware and propellant.

A recent investigation of launch opportunities between 1970 and 1980 (Sturms 1966) revealed that only the 1970 and 1973 launch windows (Table 2.1) are acceptable for a Mariner class Earth-Venus-Mercury mission. Present plans for Venus flyby missions focus around launch dates from 1970 to 1978. Further study should be given to uprating a 1970 or 1973 Venus mission to include a Mercury flyby.

3. OUTER PLANET MISSIONS

The outer planets, Saturn, Uranus, Neptune, and Pluto, orbit the Sun between 9.5 AU (Saturn) and 30 AU (Pluto during the next 30 years). Gravity assist from Jupiter (or Saturn) characteristically reduces the flight time and energy requirements of ballistic trajectories to these planets. Also, multiple planet objectives of a gravity-assist mission provide a greater scientific potential to each spacecraft launched. This factor is particularly important for outer planet missions for which flight times can be as long as 8 years even with gravity assist.

In contrast to these advantages, there are, however, several restrictions to the use of gravity-assisted trajectories for outer-planet exploration. For equal time trajectories, a gravity-assist maneuver always increases the hyperbolic approach velocity at the target planet. This is not a severe constraint for flyby missions, but for spacecraft intended to become orbiters, analysis shows that direct trajectories yield a larger weight in orbit than do gravity-assist trajectories of equal trip time. This result virtually eliminates the consideration of gravity assist for outer planet orbiter missions.

Launch opportunities for direct trajectories to the outer planets occur approximately once a year due to the Earth's orbital motion. Including a gravity assist maneuver limits these yearly opportunities to short periods of three to five years due to an additional outer planet phasing requirement. Subsequent opportunities do not reappear for a time approximately equal to the synodic period of the outertwo planets considered in the combination. A number of outer planet synodic periods are listed in Table 3.1. Since the shortest synodic period of all combinations of outer planets is about 12.5 years (Jupiter-Pluto), advanced planning of launch schedules is important if gravity-assist missions are part of an outer planet exploration program.

Table 3.1

SYNODIC PERIODS BETWEEN OUTER PLANETS CONSIDERED AS MULTIPLE MISSION TARGETS

Planet Combination	Synodic Period, years
Jupiter-Saturn	19.86
Jupiter-Uranus	13.81
Jupiter-Neptune	12.78
Jupiter-Pluto	12.46
Saturn-Uranus	45.36
Saturn-Neptune	35.87
Uranus-Neptune	171.39

Three specific spacecraft/launch vehicle examples were selected to analyze gravity assist performance. Since direct trajectories perform superior orbiter missions to the outer planets, only spacecraft designed for flyby missions are considered. The spacecraft weight, launch vehicles, and mission descriptions are summarized in Table 3.2. The Saturn V-Centaur was also considered as a potential launch vehicle, but it was eliminated after analysis showed that more than a 10,000-lb payload would be required for its effective use; i.e., it should be used for an orbiter class mission instead of a flyby class mission.

Table 3.2

SUGGESTED SPACECRAFT/LAUNCH VEHICLE EXAMPLES FOR PERFORMANCE ANALYSIS OF OUTER PLANET MULTIPLE MISSIONS

Spacecraft/Launch Vehicle	Mission Description
500-lb/Atlas -Centaur-Kick	A precursor mission with a very limited experiment/communication package for initial critical measurements.
1000-lb/Saturn 1B-Centaur	Mariner class mission with several planetary experiments excluding photography.
2500-lb/Saturn 1B (Zero Stage)-Centaur	A detailed flyby mission with a variety of sophisticated experiments and limited photography.

Factors of merit are discussed for each of the following multiple missions:

(1) Earth-Jupiter-Saturn

(2) Earth-Jupiter-Uranus and Earth-Saturn-Uranus

(3) Earth-Jupiter-Neptune and Earth-Saturn-Neptune

(4) Earth-Jupiter-Pluto.

The three factors of merit are (1) the compatibility of scientific objectives between the outer planets within each combination, (2) payload and flight time improvements to the outermost planet with gravity assist, and (3) the next series of launch opportunities of each set of missions listed.

3.1 Earth-Jupiter-Saturn

Scientific observations of Jupiter and Saturn suggest that these planets have many similar properties. The critical measurements suggested for an early flyby mission to Jupiter (Witting, Cann, and Owen 1965) could also answer some of the fundamental scientific questions about Saturn (Dickerman 1966). A compatible set of objectives for this double-planet flyby would include (1) measurement of the strength and configuration of the planetary magnetic fields, (2) initial investigation of the atmospheres including temperature, composition, and perhaps photographic data, and (3) particle and field measurements of the surrounding environment.

Figure 3.1 is a bar chart of the spacecraft weight capability of three launch vehicles for four fixed flight times to Saturn. Both direct and Jupiter-gravity-assisted trajectories are considered. The chart emphasizes potential payload improvement with gravity assist at fixed flight times. At a three-year flight time, for example, a Jupiter gravity assist provides a 118% average improvement in spacecraft weight. The smallest improvement with this flight time is 70%, or 330 lb, with the Atlas-Centaur-Kick launch vehicle.

When specific spacecraft/launch vehicle combinations are given, flight time rather than spacecraft weight is the mission parameter that can be improved with gravity assist. The flight times of each spacecraft/launch vehicle example cited in Table 3.2 are compiled in Table 3.3 for both direct

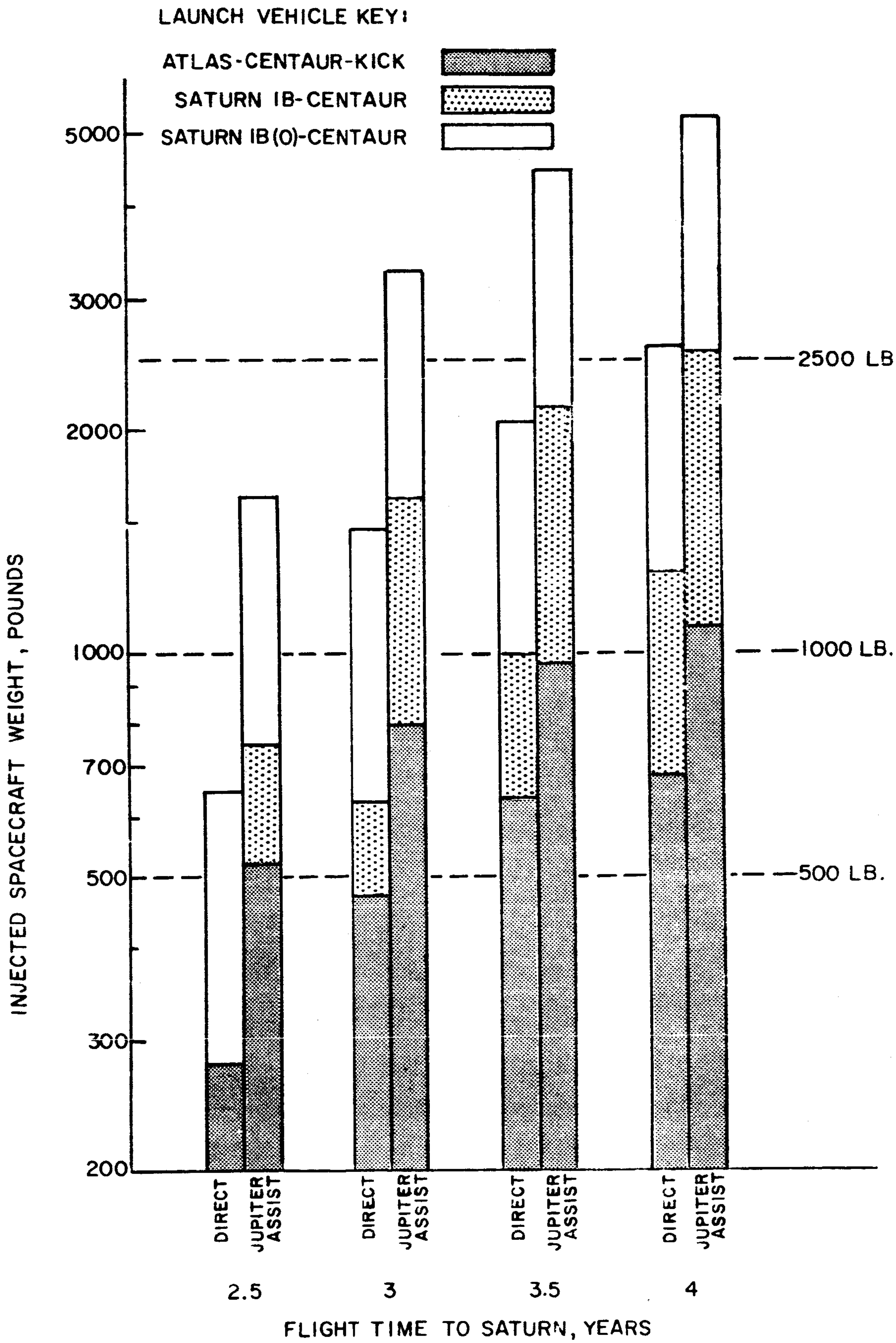


FIGURE 3.1. SPACECRAFT WEIGHT BAR CHART FOR SATURN MISSIONS

and Jupiter-assisted trajectories to Saturn.

Table 3.3

FLIGHT TIMES FOR SATURN MISSIONS

	Flight Time, years	
Spacecraft/Launch Vehicle	Saturn Direct	Jupiter Gravity Assist
500-lb/ Atlas -Centaur-Kick	3.1	2.5
1000-lb/Saturn 1B-Centaur	3.5	2.7
2500-lb/Saturn 1B (Zero Stage)-Centaur	4.0	2.8

Direct Saturn missions take more than 3 years. A Jupiter gravity assist provides an average of 24% savings in flight time for the combinations shown.

The payload improvements with gravity assist are important in the development of spacecraft design. After a spacecraft has been selected (and this usually implies a mated launch vehicle), the flight time improvements become the important parameter of gravity-assist interest. Flight time improvements will be emphasized in this discussion in order to show changes in gravity-assist performance from one outer planet target to the next with given spacecraft/launch vehicle combinations.

The next period of yearly opportunities for Jupiter-assisted trajectories to Saturn occurs from 1976 to 1979, and the best opportunity during this period occurs in 1977. After 1979, the next period of gravity-assist opportunities does not begin until 1996. Opportunities for direct trajectories are always available once every 13 months.

The commonality of objectives between Jupiter and Saturn for early flyby missions is the most attractive aspect of an Earth-Jupiter-Saturn mission. The improvement in flight time to Saturn with a Jupiter assist is also useful. The launch period from 1976 to 1979 should permit sufficient lead time to develop a spacecraft for this mission. In summary, this is one of the better outer-planet multiple missions considered.

3.2 Earth-Jupiter-Uranus and Earth-Saturn-Uranus

Similarities between Jupiter and Saturn are also shared by Uranus. For initial spacecraft investigations of Uranus' physical properties, either Jupiter or Saturn gravity assists would have compatible scientific objectives. Measurements of atmospheric temperature and composition, magnetic field strength and configuration, and the near-planet interplanetary environment would add to what is presently at best a qualitative base of information about these planets.

Figure 3.2 is a spacecraft weight bar chart for Uranus missions. With a fixed flight time and any launch vehicle shown, the use of a Saturn assist almost always doubles the direct-flight spacecraft weight. Employing a Jupiter assist at least triples the spacecraft weight and can improve it by as much as a factor of 8. Flight times to Uranus are compared in Table 3.4 for the

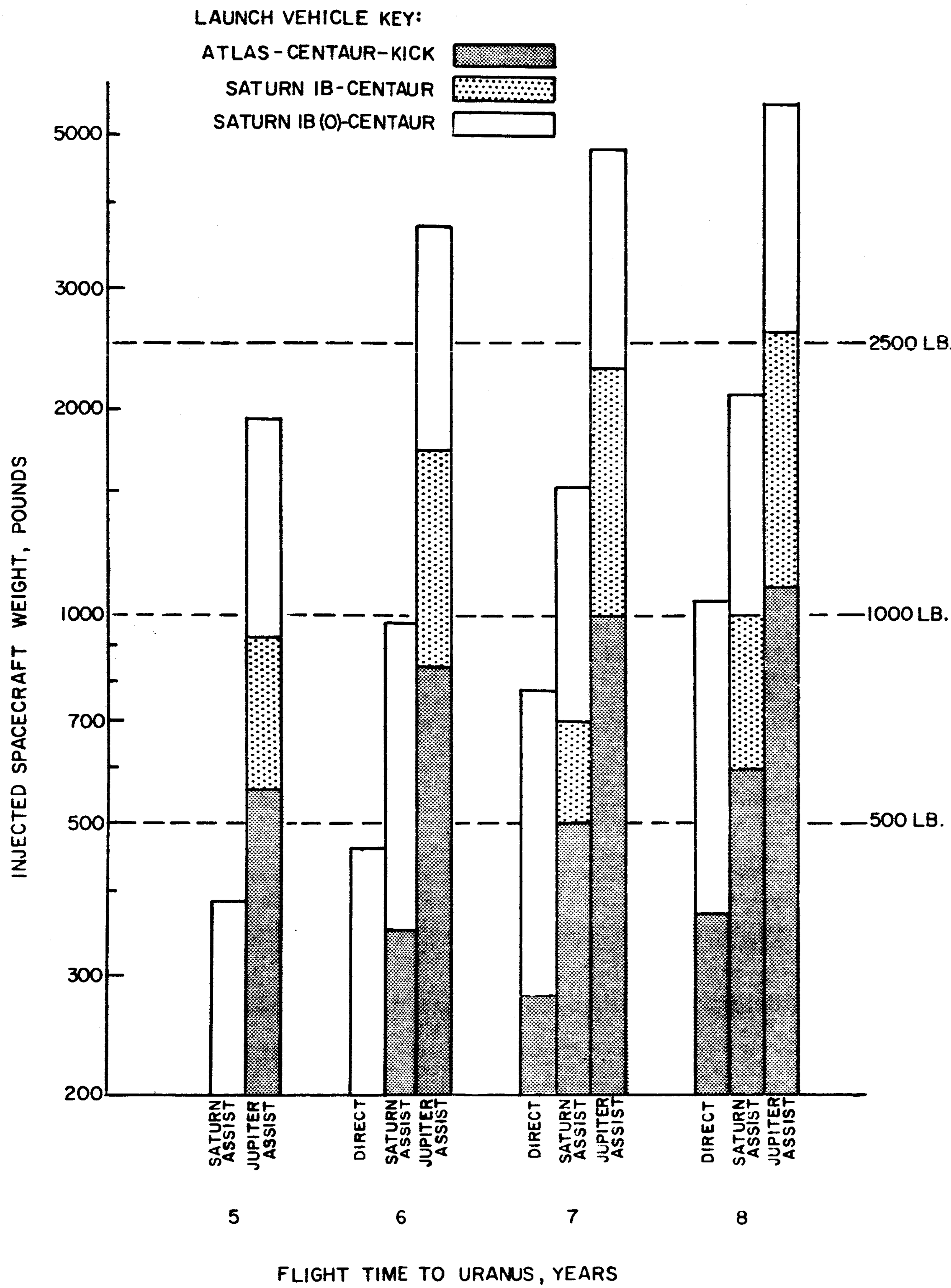


FIGURE 3.2. SPACECRAFT WEIGHT BAR CHART FOR URANUS MISSIONS

spacecraft/launch vehicle combinations specified in Table 3.2. A 500-lb spacecraft launched in direct flight by the Atlas-Centaur-Kick uses a near-Hohmann transfer to reach Uranus in 13.7 years. The other two combinations cannot reach Uranus without a gravity assist. A Saturn assist improves the 13.7-year flight time by 6.7 years, or 49%. A Jupiter gravity assist would improve the Saturn-assisted flight time by an average of 36%.

Table 3.4

FLIGHT TIMES FOR URANUS MISSIONS

Spacecraft/ Launch Vehicle	Flight Time, years		
	Uranus Direct	Saturn Gravity Assist	Jupiter Gravity Assist
500-lb/ Atlas-Centaur-Kick	13.7	7.0	4.8
1000-lb/Saturn 1B-Centaur	IE*	8.0	5.1
2500-lb/Saturn 1B (Zero Stage)-Centaur	IE*	8.9	5.3

*IE: Insufficient energy to reach Uranus.

The next period of opportunities for Saturn-assisted trajectories to Uranus occurs between 1979 and 1985. The phasing between Saturn and Uranus after 1985 prohibits any further gravity assist opportunities until 2025. The next period of opportunities for Jupiter-assisted trajectories to Uranus is

1978 to 1980. Twelve years later (1992), a similar launch period reappears.

Several interesting alternatives to Earth-Jupiter-Saturn and Earth-Jupiter-Uranus missions are available. Flandro (1966) suggests a "Grand Tour" Earth-Jupiter-Saturn-Uranus-Neptune mission to take advantage of favorable phasing between the outer planets during the late 1970s. Replacement of separate Earth-Jupiter-Saturn and Earth-Jupiter-Uranus missions with the "Grand Tour" is an interesting possibility. A penalty of about 1 additional year to reach Uranus is necessary. Launch opportunities occur in 1977 and 1978.

Another interesting alternative is a double launch of two spacecraft with one vehicle during the 1978 opportunity. Both spacecraft would travel similar trajectories to Jupiter. Small differences in each trajectory could be accomplished with midcourse control so that Jupiter approach conditions would be different. One spacecraft could then be perturbed to intercept Saturn, and the other would be deflected to intercept Uranus (without a flight time penalty). If either spacecraft failed early in flight, the other could be used to pursue the most favorable target.

Questions arise from either alternative. Are midcourse requirements reasonable? What is the probability of success? Does this alternative provide the maximum scientific return per unit cost? Examining these and other alternatives and answering the questions that arise require a detailed study of outer-planet multiple missions.

3.3 Earth-Jupiter-Neptune and Earth-Saturn-Neptune

So little is known about Neptune that it is difficult to postulate any more than basic scientific questions for initial intercept missions. Atmospheric and magnetic field measurements seem most important. As with Uranus, these objectives appear compatible with those of Jupiter and Saturn.

Figure 3.3 is a spacecraft weight bar chart for Neptune missions. Spacecraft weight improvement with gravity assist is even better than gains cited for Uranus multiple missions. Flight times for the suggested spacecraft/launch vehicle combinations are compared in Table 3.5. None of these combinations can reach Neptune on direct ballistic trajectories. Even with a Jupiter gravity assist, the flight time is more than 7 years. However, by increasing the launch vehicle capability within each combination, some further reduction can be made in flight time. For example, adding a kick stage to the Saturn 1B (zero stage)-Centaur, the flight time of a 2500-lb spacecraft would be reduced to 5.6 years with a Jupiter gravity assist.

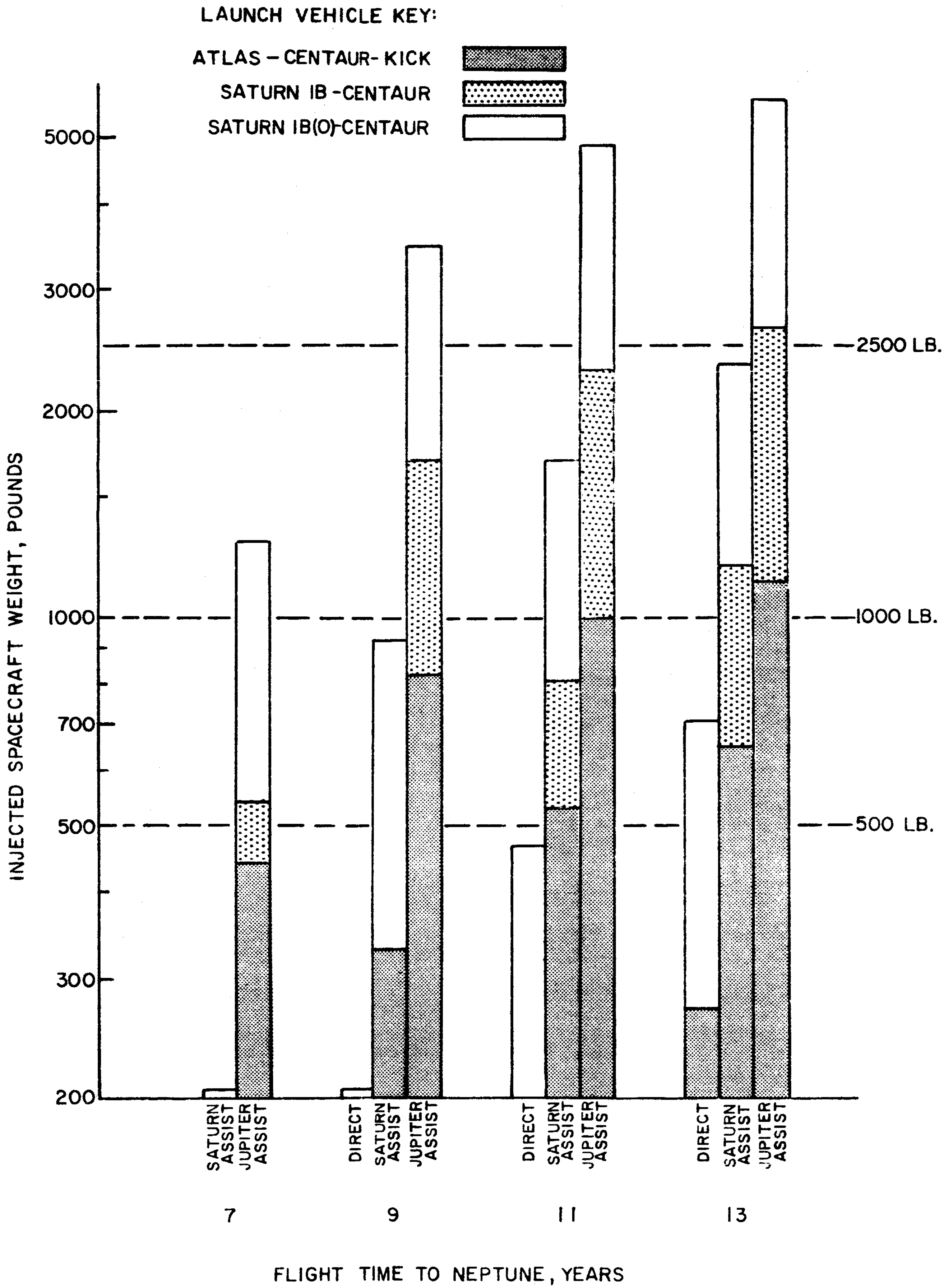


FIGURE 3.3. SPACECRAFT WEIGHT BAR CHART FOR NEPTUNE MISSIONS

Table 3.5

FLIGHT TIMES FOR NEPTUNE MISSIONS

Spacecraft/Launch Vehicle	Flight Time, years		
	Neptune Direct	Saturn Gravity Assist	Jupiter Gravity Assist
500-lb/ Atlas -Centaur-Kick	IE*	10.7	7.2
1000-lb/Saturn 1B-Centaur	IE*	12.0	7.7
2500-lb/Saturn 1B (Zero Stage)-Centaur	IE*	13.4	8.0

*IE: Insufficient energy to reach Neptune.

The next period of yearly opportunities for Jupiter-assisted Neptune missions is 1979 to 1981; a similar launch period reappears in 1992. There are also five opportunities for Saturn-assisted trajectories to Neptune between 1979 and 1985. After 1985, the next launch period for these trajectories does not start until 2015.

3.4 Earth-Jupiter-Pluto

Pluto is presently regarded as a member of the terrestrial planet family of our solar system. Very little is known about this planet. The most important questions about Pluto that can be answered by initial flyby spacecraft are concerned with accurate measurements of its diameter, mass, and rotation (rate and orientation) and with determinations of whether it has an atmosphere.

Combining the Jupiter and Pluto scientific objectives does not appear advantageous. The primary motivation for a multiple mission to these planets is the improvement in flight time gained with a Jupiter assist. Flandro (1966) reports flight times as low as 7 years with a Jupiter assist and an ideal velocity of 57,600 ft/sec during a favorable 1977 launch window. Direct flight to Pluto with the same energy takes 42 years. Even a Saturn V-Centaur with much higher energy, cannot match the 7-year flight time of gravity assist.

The 1977 launch opportunity may be premature for a Pluto precursor mission. However, the synodic period of Jupiter/Pluto is comparatively short, 12.5 years (see Table 3.1), and another favorable opportunity for the Jupiter-assisted Pluto mission occurs in 1989 or 1990. The Pluto intercept point (1997) for the 1990 launch is also slightly closer to the Sun and the ecliptic plane than it is for the 1977 launch. There still remains, however, the 7-year trip time, and low-thrust propulsion may be competitive by 1990.

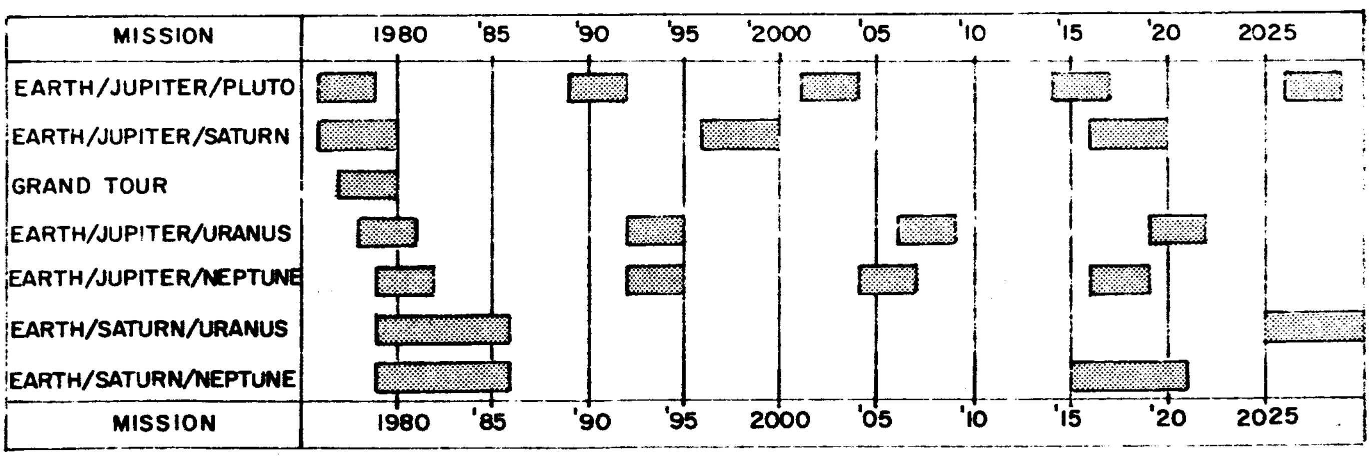
All the launch opportunities for the outer-planet multiple missions discussed are summarized in Table 3.6. Below the table a graphical distribution of opportunity periods is shown for gravity assisted outer planet missions between 1975 and 2030. The fact that all the next opportunities occur around 1980 is a coincidence. After 1980, opportunities do not occur together but reappear anywhere from 1989 to 2025. Since such a large number of multiple outer planet opportunities occur at the same time in the late 1970s, judicious planning will be required to single out those missions most useful to the space program.

Table 3.6

PERIODS OF YEARLY LAUNCH OPPORTUNITIES FOR SELECTED GRAVITY ASSISTED OUTER PLANET MISSIONS

Mission	Next Launch Period	Start of Following Period
Earth/Jupiter/Saturn	1976-1979	1996
Earth/Jupiter/Uranus	1978-1980	1992
Earth/Saturn/Uranus	1979-1985	2025
Earth/Jupiter/Neptune	1979-1981	1992
Earth/Saturn/Neptune	1979-1985	2015
Earth/Jupiter/Pluto	1976-1978	1989

DISTRIBUTIONS OF GRAVITY ASSIST OUTER PLANET MISSION OPPORTUNITY PERIODS*
BETWEEN 1975 AND 2030



* PERIODS BEGINNING AFTER THE LATE 1970S ARE BASED ON SYNODIC PERIOD RELATIONS AND MAY BE IN ERROR BY ONE OR TWO YEARS

4. OUT-OF-THE-ECLIPTIC MISSIONS

Planetary unmanned missions have already and will continue to supply measurements of the interplanetary environment in the ecliptic plane. The purpose of out-of-ecliptic (OOE) missions is to provide a three-dimensional picture of interplanetary space.

In a recent study of interplanetary missions, Roberts (1965) discussed direct OOE missions. Ideal velocity requirements increase rapidly for trajectories of high heliocentric inclination, as shown by the direct curve in Figure 4.1. In order to reach a desired solar latitude with the absolute minimum ideal velocity, Roberts notes that trajectories for such missions are constrained to narrow bands of space less than 1 AU from the Sun. Even so, OOE missions to latitudes above 45° are beyond the capability of a Saturn V-Centaur-Kick launch vehicle. The use of a Venus, Mars, or Jupiter gravity assist was studied to reduce the ideal velocity requirements for higher latitudes and to provide OOE trajectories that encompass a larger portion of the solar system.

Maximum post-assist inclinations (latitudes) were calculated as a function of ideal velocity using circular ecliptic orbits for Venus and Mars. The results are compared with the direct flight curve in Figure 4.1. This analysis predicts a maximum inclination of 10.5° with a Venus gravity assist and 8° with a Mars assist. Minovitch (1965), however, obtained somewhat better results by using three-dimensional

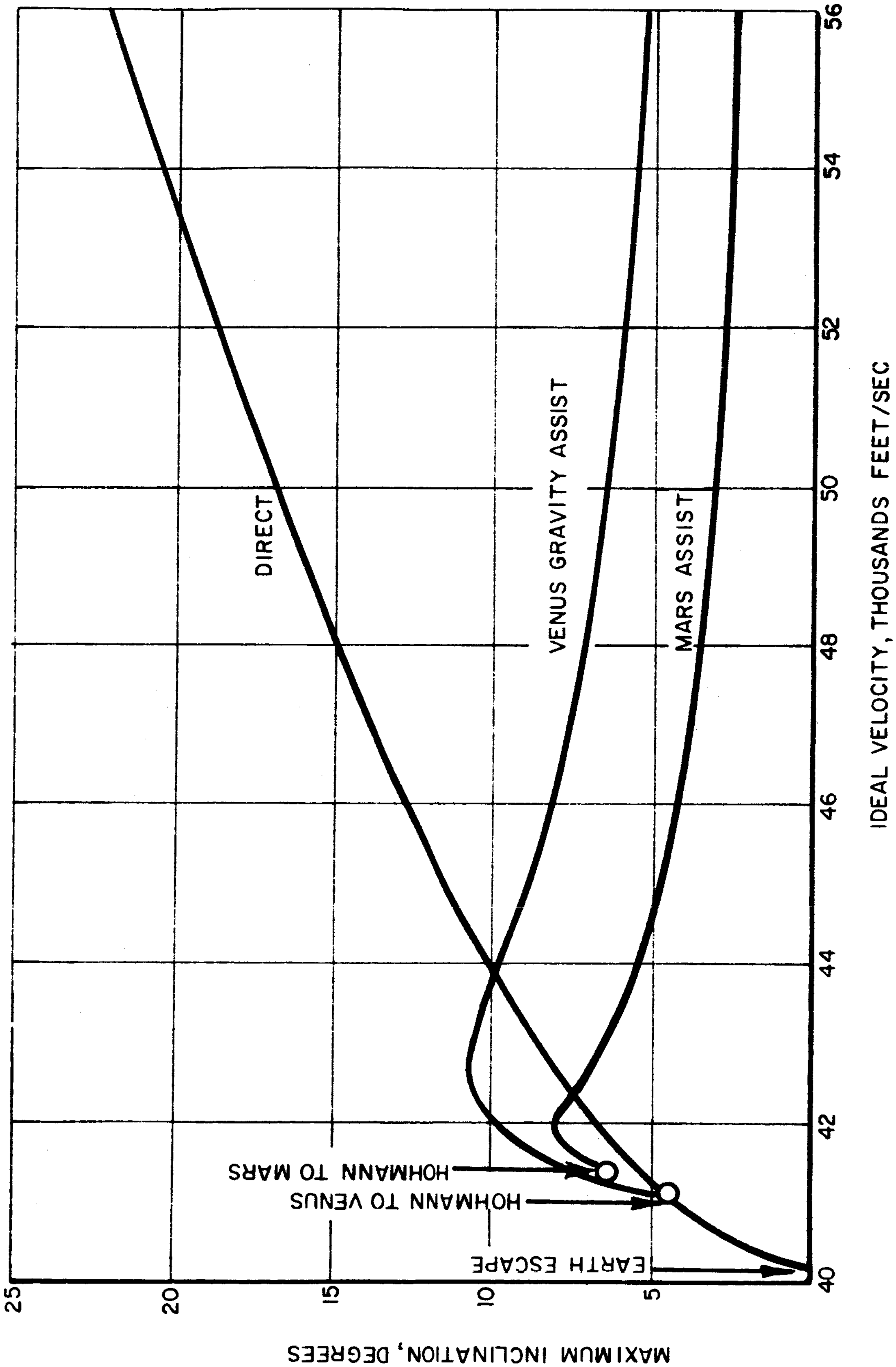


FIGURE 4.1. OUT-OF-ECLIPTIC ENERGY REQUIREMENTS

planet orbits. He states, "Mars and Venus can be used to obtain inclinations of about 10 to 15°. The maximum distances out of the ecliptic plane are about 23 million miles (0.223 AU)." Ideal velocities of about 42,000 ft/sec are required.

Although a 15° inclination mission will provide initial useful information about low-latitude OOE regions, higher inclinations should be attained before a complete picture of interplanetary environment can be expected. Trajectories with a 90° inclination could provide data at all solar latitudes. Hunter (1964) points out, however, that an ideal velocity of about 144,000 ft/sec would be required to place an interplanetary probe in a 90°/1 AU direct orbit. Yet Jupiter with its large mass can perturb an interplanetary probe to escape at 90° to the ecliptic plane for an ideal velocity of 65,000 ft/sec. This energy requirement could be met by a Saturn (zero stage)-Centaur-Kick launch vehicle and a 1100-lb payload.

Figure 4.2 is a performance graph of Jupiter-gravity-assisted 90° inclined trajectories. The data were prepared by Porter, Luce, and Edgecombe (1965) in a study of Jupiter-assisted OOE trajectories. The distance above the ecliptic at a point directly over the Sun is plotted as a function of ideal velocity. In addition to the 90°/solar system escape point noted on the curve, two other points are of interest. The first is at an ideal velocity of about 54,400 ft/sec.

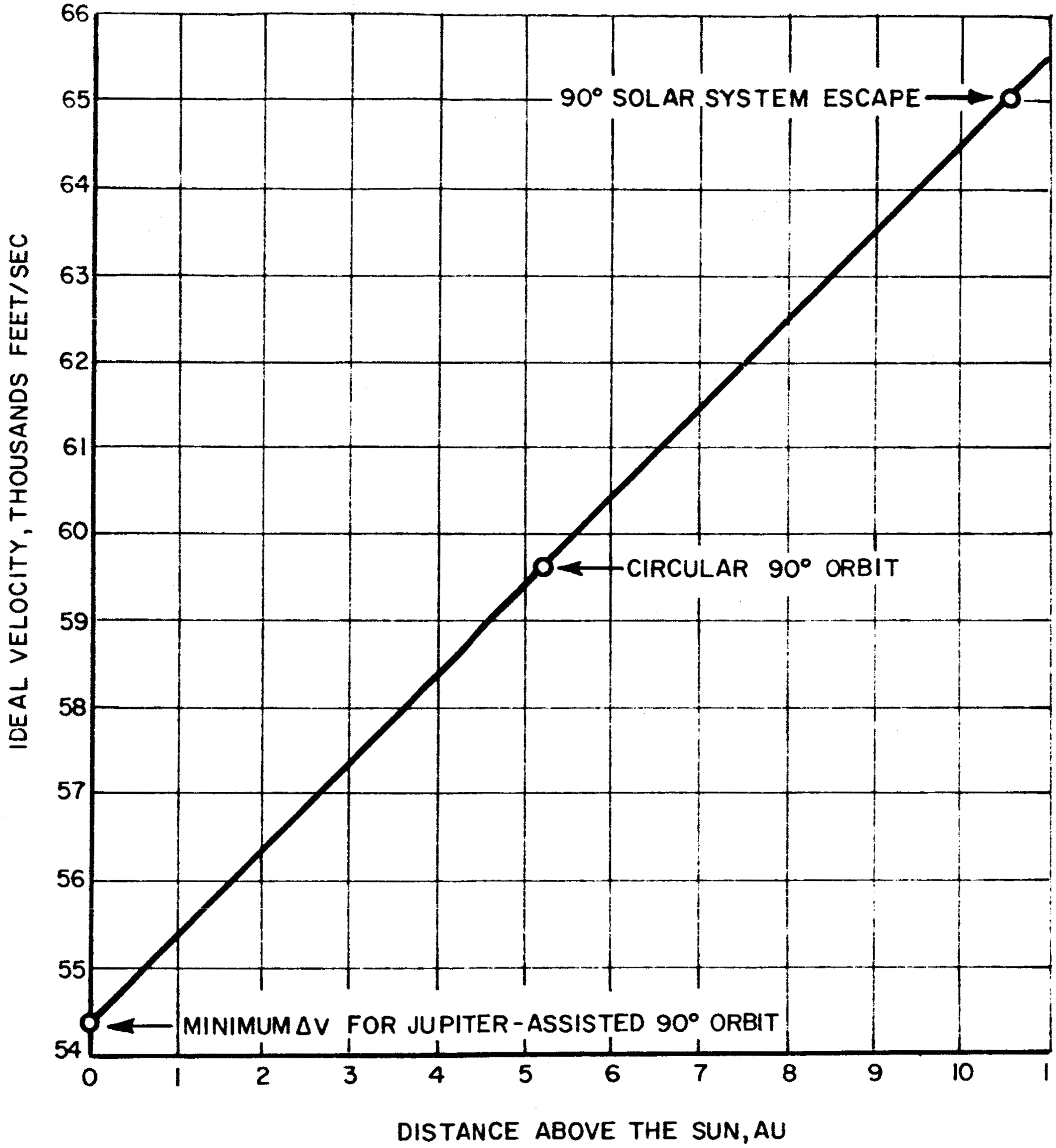
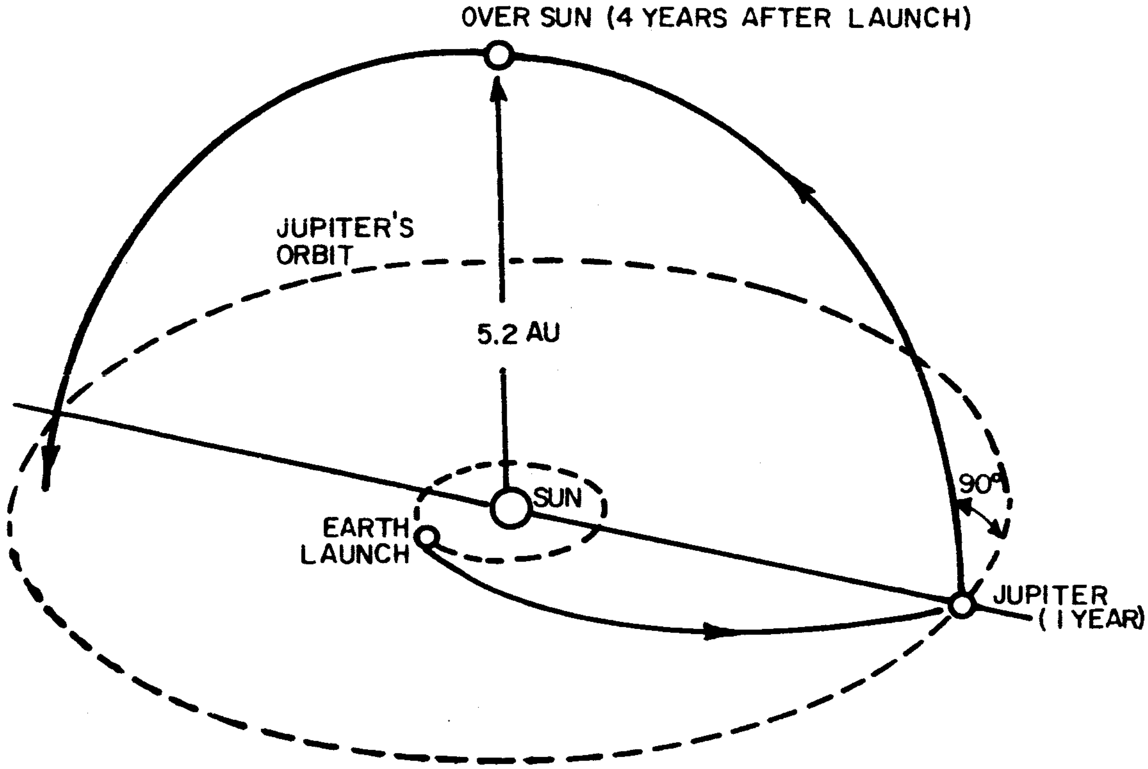


FIGURE 4.2. DISTANCE ABOVE THE SUN FOR JUPITER-ASSISTED 90° ORBITS

Porter et al point out that 90° orbits are not possible with Jupiter assist below this energy; they explain that such a maneuver requires a hyperbolic approach velocity in excess of Jupiter's heliocentric velocity. The second point of interest in Figure 4.2 occurs at 59,600 ft/sec. At this energy, Jupiter is capable of perturbing an Earth-launched probe into a 90°/ 5.2 AU circular orbit. This trajectory is depicted three-dimensionally in Figure 4.3. Note that the trip time required to arrive directly over the Sun is about 4 years.

In another study Minovitch (1965) presented detailed launch opportunity data for Jupiter-assisted OOE missions. His results are summarized in Table 4.1. These trajectories have been designed to minimize trip time and ideal velocity. Launch opportunities occur yearly. A maximum distance above the ecliptic plane of more than 2 AU is attained. In most cases a distance of more than 1 AU over the Sun is also possible. During a few of the opportunities perihelia go as low as 0.02 AU, making additional solar probe objectives possible. Other opportunities have perihelia in the neighborhood of 1 AU, suggesting an Earth flyby as the probe crosses the ecliptic plane. In summary, Jupiter-assisted trajectories make it possible to add planetary, solar probe, or even solar system escape objectives to OOE interplanetary investigations.



TRAJECTORY DATA:

LAUNCH OPPORTUNITIES - ONE/YEAR FOR 1970-1980
IDEAL VELOCITY = 59,600 FEET/SEC
JUPITER APPROACH VELOCITY = 18.5 KM/SEC
JUPITER MISS DISTANCE = 125,000 KM
FLIGHT TIME TO ECLIPTIC POLE = 4 YEARS

FIGURE 4.3. EARTH-JUPITER-90°/5.2AU ORBIT ILLUSTRATION

Table 4.1

LAUNCH DATA* FOR EARTH-JUPITER-90°/OOE MISSIONS

Launch Window	Ideal Velocity, ft/sec	Minimum Jupiter Miss Distance 10^3 kilometers	Max. Distance above the Ecliptic, AU	Perihelion Range, AU	Max. Trip Time to Perihelion, years
10/25-11/12/67	55,100	593	1.63	0.02-0.46	3.92
11/22-12/10/68	"	563	-1.95**	0.19-0.73	4.08
12/25/69-1/10/70	"	453	-2.27	0.42-0.98	4.16
1/25-2/10/71	"	431	-2.32	0.48-1.04	4.07
2/27-3/16/72	"	448	-2.06	0.38-0.82	3.80
4/2-4/20/73	"	497	-1.49	0.08-0.42	3.45
5/11-5/29/74	56,275	369	-1.97	0.39-0.75	3.56
6/19-7/7/75	"	407	1.68	0.21-0.60	3.50
7/23-8/10/76	"	415	1.73	0.22-0.60	3.62
8/27-9/14/77	"	406	2.08	0.35-0.81	3.88
9/29-11/17/78	"	390	2.43	0.57-1.06	4.17

*Data by Minovitch (1965).

**Minus sign indicates below the ecliptic plane.

5. SOLAR PROBES

A principal advantage of solar probe missions is that they provide local measurements of the solar corona. Smith, Dickerman, and Thornton (1965) state that "the energy spectra and flux of solar protons and M-region particle streams, and the strength and direction of associated magnetic fields, can only be discovered by in situ measurements." Measurements within 0.1 AU of the Sun could also lead to a better understanding of the behavior of objects passing close to the Sun, e.g., the recent comet Ikeya-Seki. Temperature and radiation data would be of further use in the design of such advanced solar probes as a synchronous solar orbiter, which would have to function extensively at 0.17 AU.

The ideal velocity requirement for a direct Hohmann transfer to 0.1 AU is about 70,000 ft/sec. The high-energy Saturn 1B (zero stage)-Centaur-Kick launch vehicle has an ideal velocity capability of about 72,000 ft/sec with a 500-lb spacecraft. The energy required to kill the Earth's orbital speed and drop to a solar impact is more than 100,000 ft/sec. Significant reductions in ideal velocity for close solar-probe missions can be achieved with a Jupiter gravity assist. Figure 5.1 is a performance graph of Jupiter-assisted solar probe trajectories. Total trip time is plotted against ideal velocity for curves of constant Jupiter miss distance (measured here from the center of the planet) and final perihelion. It is observed that perihelia ranging from 0.3 AU to solar impact

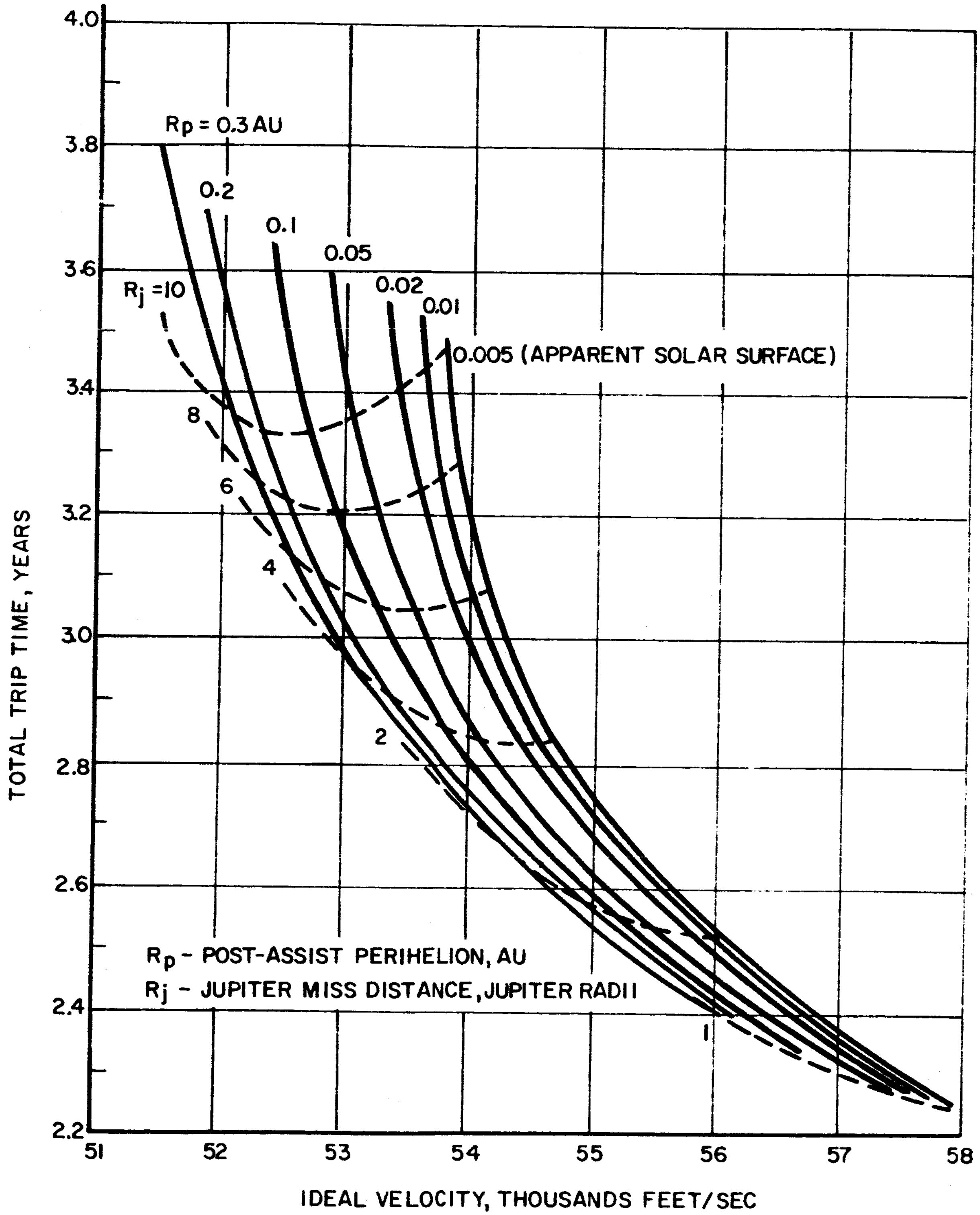


FIGURE 5.1. JUPITER-ASSISTED SOLAR PROBE PERFORMANCE

are available for no more than 54,000 ft/sec and a 3.2-year flight time. Admittedly, three-year trip times affect spacecraft reliability. Some reduction in flight time is possible at the expense of added energy. For example, as shown in Figure 5.1, solar impact is possible in less than 2.3 years for an ideal velocity of 57,500 ft/sec.

The possibility of a Venus gravity assist has also been investigated. Although performance cannot be expected to equal a Jupiter perturbation, the problems of long flight time and asteroid hazards are avoided. Results of our studies indicate that Venus-assisted trajectories to about 0.3 AU pose only moderate launch vehicle requirements (Niehoff 1965). For example, a 1000-lb probe/ Atlas -Centaur combination with a Venus assist would reach 0.3 AU in about 120 days.

Casal and Ross (1965) have suggested an interesting double Venus assist to reduce the perihelion to less than 0.2 AU for about 46,100 ft/sec instead of 52,800 ft/sec with a single assist; that is, two flybys of Venus are executed about 450 days apart to reach a closest solar approach of 0.196 AU. The total trip time to this perihelion is less than 2 years. It is interesting to note that the probe spends about 15 days within 0.3 AU on the second solar pass. During this time the relative motion of the Sun's surface to the probe is only 3°/day positive. This allows the probe to view about 45° of the solar surface from less than 0.3 AU, in addition to collecting in situ data down to about 0.2 AU. The guidance requirements of a double Venus assist have not been analyzed but could be a drawback to this mission. On the other hand, a double Venus flyby, corona measurements to 0.2 AU, solar surface astronomy from less than 0.3 AU, and a 6,500 ft/sec saving in ideal velocity may be the ingredients that make a solar probe multiple mission highly worthwhile.

Figure 5.2 is an energy versus final perihelion comparison between direct, single Venus-assisted and constant trip time Jupiter-assisted solar probe trajectories. Note that Venus-assisted trajectories continue to have smaller perihelia than direct trajectories above the energy levels cited. Venus-assisted trajectories are suggested for initial solar probes to perihelia as low as 0.2 AU.

If chemical propulsion is used, it remains apparent that regions from 0.1 AU to the solar surface can only be reached with a Jupiter assist. Launch opportunities for Jupiter/solar probes are frequent; they occur about once a year. A detailed study of such opportunities between 1967 and 1978 has been presented by Minovitch (1965). Witting, Cann, and Owen (1965) point out that Jupiter-assisted solar probe trajectories are ideal for critical measurements on early Jupiter missions. Coupled with Jovian objectives, the Jupiter-assisted solar probe is an attractive multiple mission and deserves further attention.

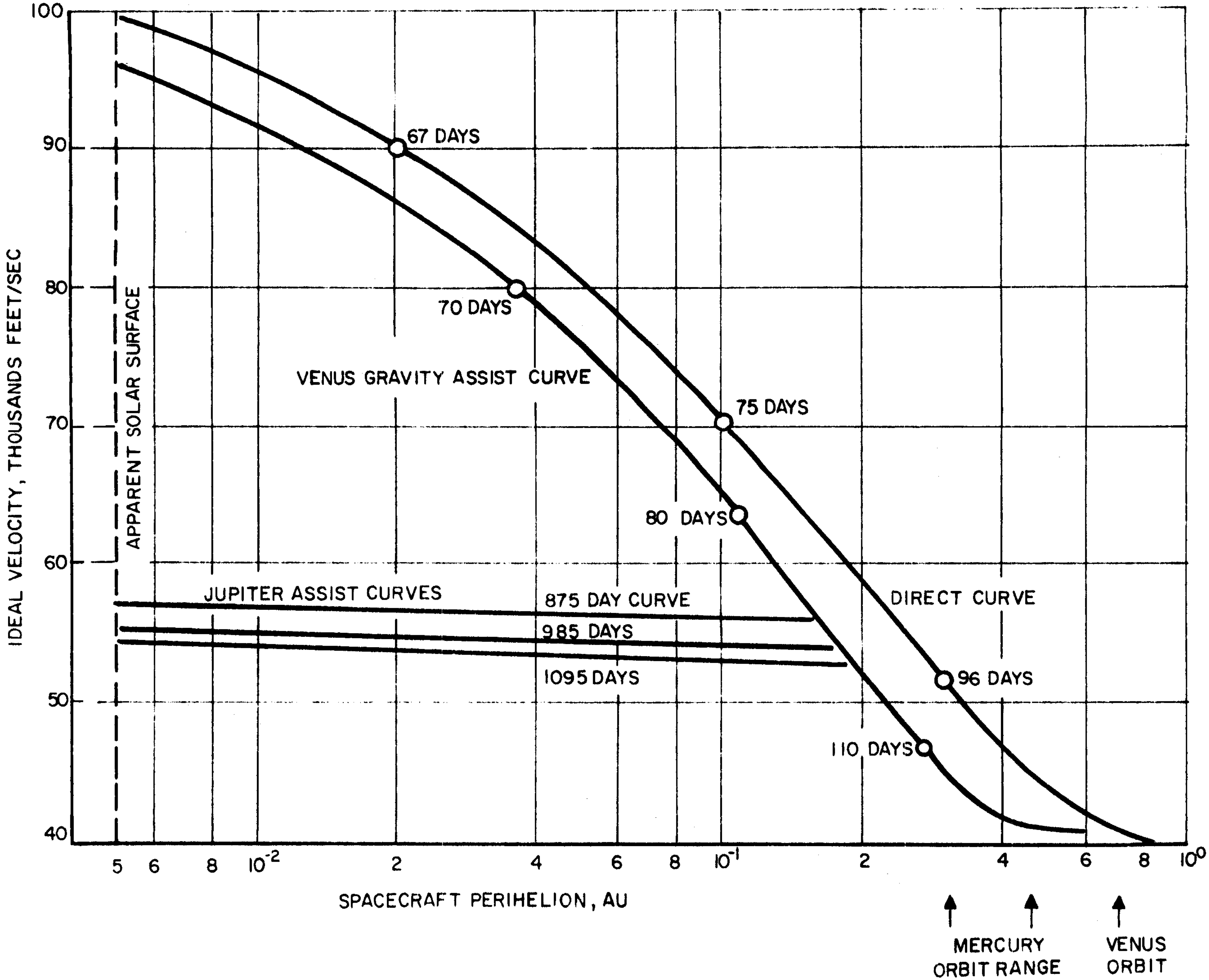


FIGURE 5.2. SOLAR PROBE ENERGY REQUIREMENTS

6. RECONNAISSANCE MISSIONS

Reconnaissance missions are defined as flyby missions of one or more planets followed by a return to Earth. These multiple missions are applicable to both manned and unmanned excursions. For manned reconnaissance missions, Earth rendezvous and recovery are of course implied. For unmanned missions, an Earth return flight could be important for one of two reasons: it might be more economical to relay large amounts of collected data during a near-Earth pass rather than from a great distance, or the recovery of the spacecraft itself may be a mission objective.

Minovitch (1963) has studied in some detail a number of reconnaissance missions involving the terrestrial planets Venus, Earth, and Mars. Table 6.1 summarizes some launch opportunity and trajectory results of his analysis. The Earth-Venus-Earth missions have total flight times of about 1 year. Earth-Mars-Earth flights (without added impulse at Mars) are unattractive because of their long trip times of about 3 years. The Earth-Venus-Mars-Earth missions seem practical since two planet flybys are possible with trip times of less than 2 years. All missions can be executed with ideal velocities of less than 43,500 ft/sec. These energy requirements permit unmanned Mariner class missions with an Atlas-Centaur launch vehicle.

One other reconnaissance flight was considered: the Earth-Jupiter-Earth mission for exploration of Jupiter and the asteroid belt. Figure 6.1 is a polar plot of the round trip

Table 6.1

SOME IMPORTANT PROPERTIES* OF TERRESTRIAL PLANET RECONNAISSANCE MISSIONS

Mission	Launch Date	Ideal Velocity, ft/sec	Miss Distance kilometers		Hyperbolic Capture Velocity at Earth, km/sec	Total Trip Time, days
			1st Assist	2nd Assist		
Earth-Venus-Earth	8/20/70	41,425	726	N/A	7.13	365
	4/ 3/72	42,150	3,983	N/A	8.18	375
	11/ 4/73	42,225	5,344	N/A	7.90	385
Earth-Mars-Earth	6/ 8/71	42,450	2,251	N/A	5.85	1,112
	8/20/73	43,200	7,024	N/A	6.56	1,028
Earth-Venus-Mars-Earth	8/12/70	41,725	3,848	6,590	9.34	622
	5/27/72	42,675	6,552	1,249	13.04	470

*Data prepared by Minovitch (1963).

TRAJECTORY DATA:

OPPORTUNITIES - ONE/YEAR FOR 1970 - 1980
IDEAL VELOCITY = 53,800 FEET/SEC
JUPITER MISS DISTANCE = 15,900 KM
VHP AT EARTH = 10.5 KM/SEC
TOTAL TRIP TIME = 2.8 YEARS

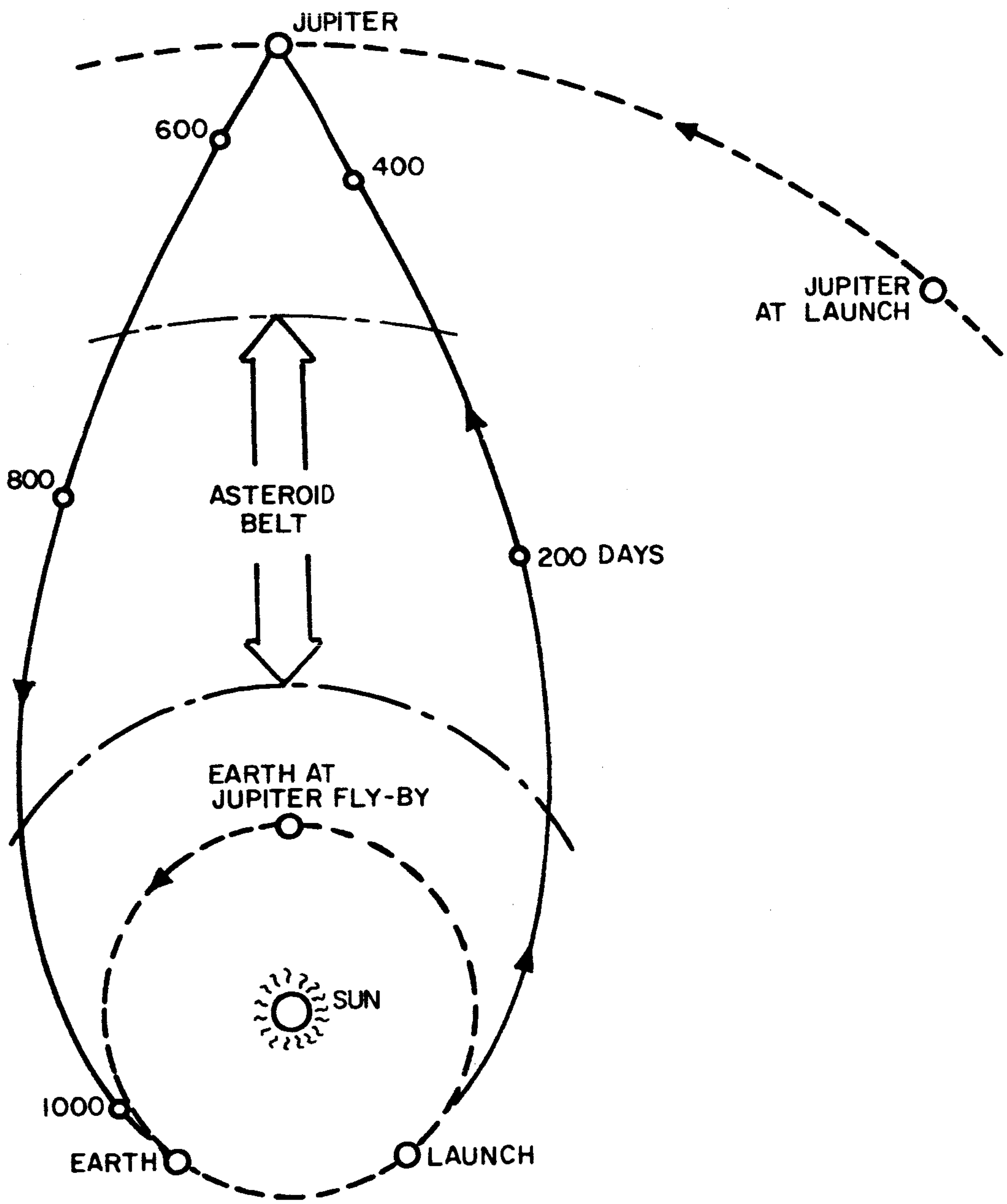
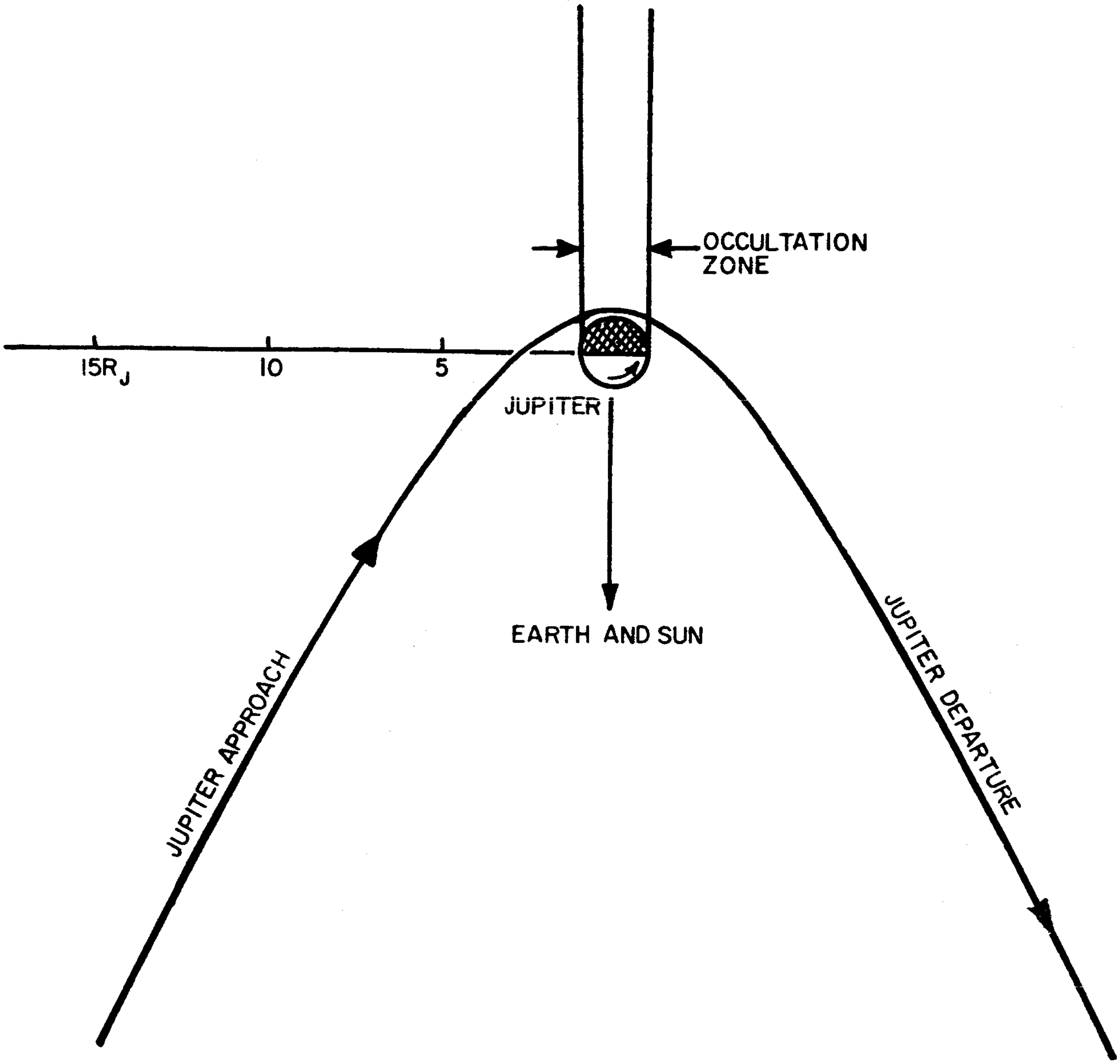


FIGURE 6.1. EARTH-JUPITER-EARTH TRAJECTORY ILLUSTRATION

trajectory. The close-approach flyby trajectory at Jupiter is also shown in Figure 6.2. The ideal velocity requirement is less than 54,000 ft/sec, which permitted payloads in excess of 1500 lb with a Saturn 1B-Centaur. Communication distance to Earth during Jupiter encounter is minimized. In order to achieve an Earth-intercept return trajectory, a very close pass is required at Jupiter, i.e., 15,900 km, or about 0.22 Jupiter radii from the optical surface. The near miss promises better results for all the experiments suggested by Witting, Cann, and Owen (1965) and, in addition, permits a search for the postulated proton radiation belt, which might exist within two Jupiter radii from the planet center. The return trajectory to Earth is a mirror image of the outbound flight. Hyperbolic capture velocity at Earth is about 10.5 km/sec. This mission would be an effective combination of a detailed Jupiter flyby and an asteroid fly-through Earth-return mission (Greenspan 1966).

It is worthwhile to briefly discuss the Earth recovery problem. The hyperbolic Earth capture velocities (VHP) cited in this section have for the most part not exceeded 10 km/sec. A VHP of 10 km/sec would yield an atmospheric entry velocity of about 50,000 ft/sec. Hunter (1965) pointed out that killing this reentry velocity would require an energy dissipation per unit mass of approximately twice that planned for the present Apollo spacecraft. This entry is, however, still within the useful range of atmospheric braking. Another study by Yoshikawa and Wick (1964) concludes that aerodynamic braking is favored



TRAJECTORY DATA:

CLOSEST APPROACH = 15,900 KM OR 0.22R_J
OCCULTATION TIME = 45 MINUTES
PERIJOVE VELOCITY = 59.4 KM/SEC.
DISTANCE TO EARTH = 4.2 AU

NOTE: R_J -JUPITER RADIUS

FIGURE 6.2. JUPITER FLY-BY ILLUSTRATION (RECONNAISSANCE MISSION)

over combined atmospheric and rocket braking for conical bodies for entry velocities up to 60,000 ft/sec.

7. ASTEROID MISSIONS

A sample distribution of 1500 numbered asteroids in radius and latitude on March 20, 1973 is shown in Figure 7.1 (Narin 1965). The asteroid belt extends from about 1.7 to 4.0 AU in radius and $\pm$ 16° out of the ecliptic plane in latitude. Three types of missions have either primary or secondary asteroid objectives: (1) Asteroid fly-throughs to outer planets and the outer solar system (beyond 4 AU), (2) detailed asteroid belt fly-throughs that can collect asteroid particles and return to Earth, and (3) intercept/rendezvous missions to the larger individual asteroids. The purpose of this section is to determine whether either Mars- or Jupiter-gravity-assisted trajectories would provide useful benefits to these types of missions.

The first spacecraft to penetrate the asteroid belt will probably be a precursor to outer-planet missions. The primary objectives include testing the spacecraft design for deep space operation and determining the spacecraft hazards imposed by the asteroid belt. It would therefore be desirable to increase the spacecraft aphelion as far into the asteroid belt as possible. With a given ideal velocity capability, this can be accomplished with a Mars gravity assist. Figure 7.2 is a plot of ideal velocity versus final aphelion for direct and Mars-assisted trajectories. By using a 500-lb/Atlas-Centaur combination with an ideal velocity capability of 44,800 ft/sec, the asteroid belt penetration (aphelion) is increased from

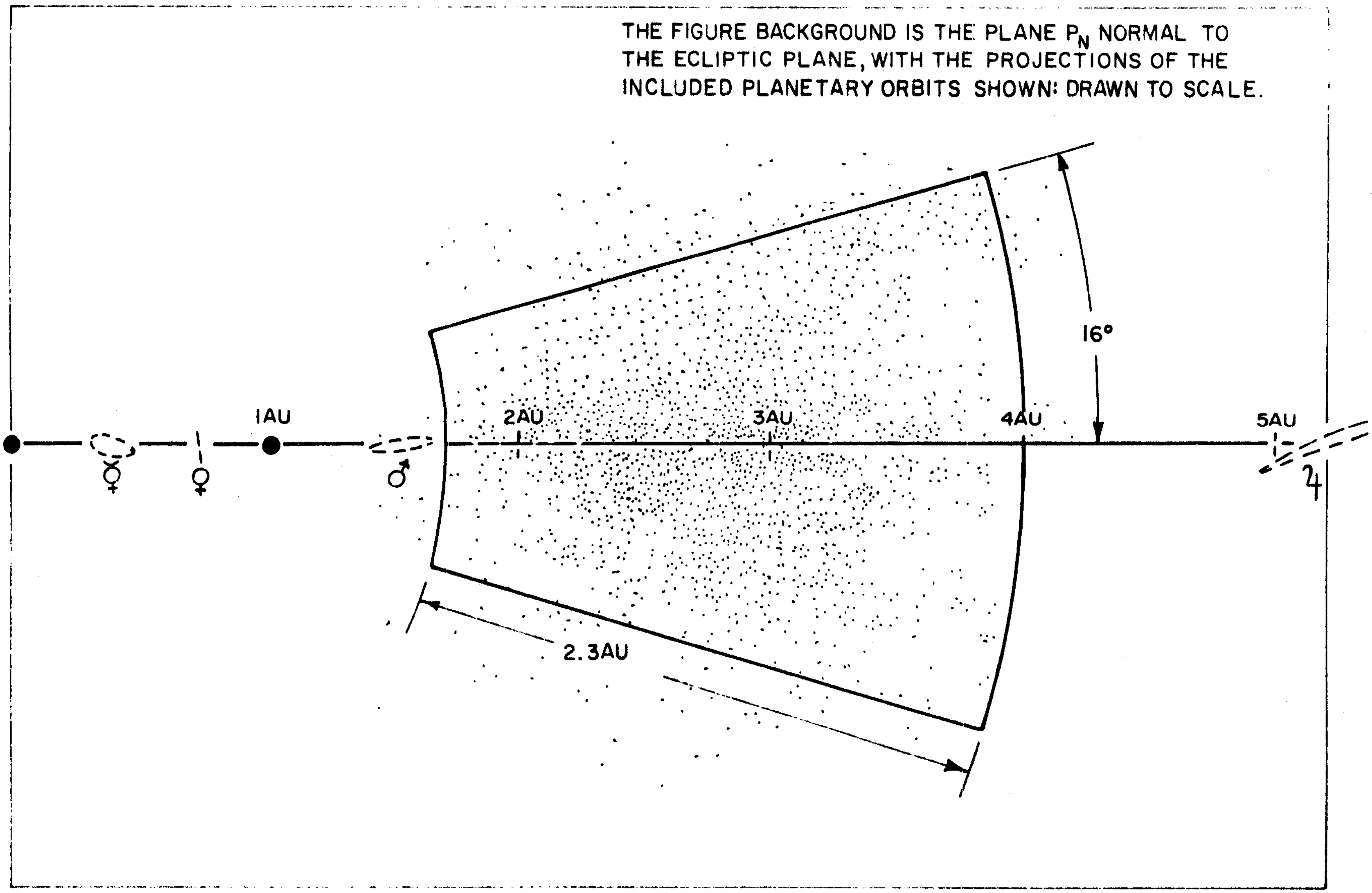


FIGURE 7.1. DISTRIBUTION OF 1500 NUMBERED ASTEROIDS IN β AND R ON 3/20/73

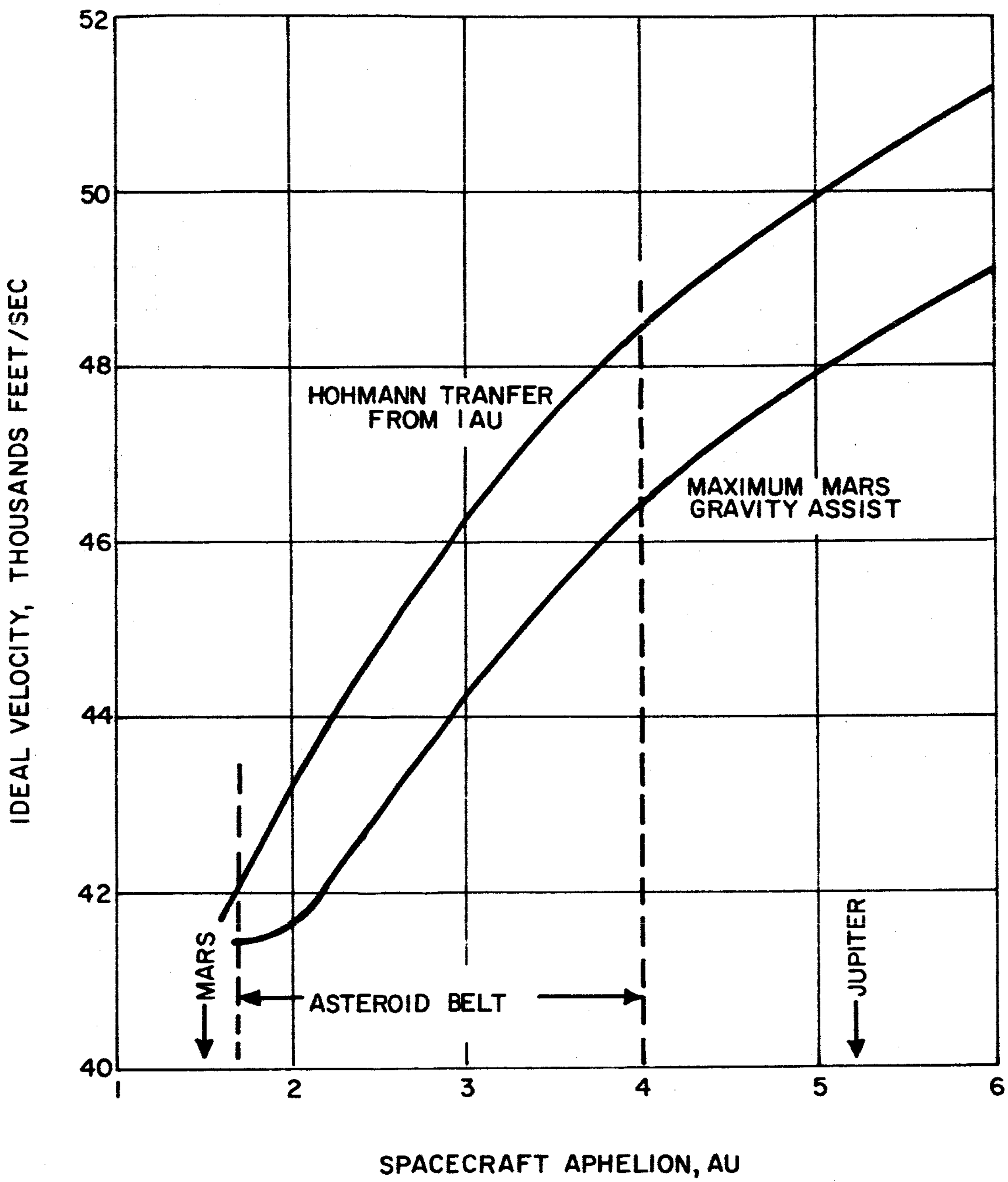


FIGURE 7.2. ASTEROID BELT PENETRATION

2.5 to 3.2 AU with a maximum Mars assist, i.e., a grazing Mars approach. For later asteroid fly-through missions with outer-planet intercepts, Mars assists are not suggested. Opportunities for acceptable Earth, Mars, and outer-planet phasing are rare; VHPs at Mars are doubled and added guidance requirements are probably not justified by the small reduction in flight time (Niehoff 1965).

Detailed asteroid belt fly-through missions will probably follow these early probes. Determination of structure, composition, and distribution of asteroidal particles and an investigation of interaction processes would be among the objectives of scientific investigations. Technological requirements for such missions are discussed in detail by Greenspan (1966). He suggests a detailed asteroid fly-through mission to 3.2 AU with an Earth recovery of collected particle samples three years after launch. A Jupiter-assisted mission similar to the Earth-Jupiter-Earth reconnaissance mission discussed in Section 6 would also encompass the detailed fly-through objectives (including sample return) as well as a detailed flyby of Jupiter. A trip time of 2.8 years is slightly shorter than the 3.2-AU mission, but the energy and the communication distance are higher. Yet the potential of the multiple mission does suggest further study of this mission, if either the detailed asteroid fly-through or the close Jupiter flyby mission is of planning interest.

Rendezvous missions to the larger asteroids would be one of the more important single contributors to an understanding of the origin of the asteroid belt and its bearing on the evolution of the solar system. A study of direct asteroid fly-by missions has already been completed (Astro Sciences 1964). One disturbing result was that minimum energy trajectories to individual asteroids have hyperbolic approach velocities (VHP) that preclude a rendezvous maneuver at intercept. VHPs for Eros, Vesta, Ceres, and Juno average about 7 km/sec for launch opportunities between 1970 and 1985. Missions to Pallas have average VHPs of about 13 km/sec, and Icarus VHPs average a high 30 km/sec.

In order to effect asteroid rendezvous missions with chemical propulsion and reasonable mass fractions, these VHPs should be below 5 km/sec. VHPs can be reduced if plane changes that can be made align the spacecraft trajectory plane with the asteroid orbit plane. The addition of Mars or Jupiter gravity assist was considered for the required plane changes. A Mars assist is only worthwhile for rendezvous with Eros. VHPs as low as 1 km/sec are possible, although some additional impulse (less than 1 km/sec) is probably necessary during gravity assist. Flight time with Mars assist could be as long as 500 days compared with 175 days direct. No launch opportunities for an Earth-Mars-Eros rendezvous missions were found until 1984.

Jupiter-assisted trajectories looked promising for rendezvous missions to the higher inclined asteroids, Pallas and Icarus (whose orbit is also exceptionally eccentric). Jupiter-assisted trajectories to the trojan asteroids are not recommended, since their orbits are similar to Jupiter's which makes post-assist flight times excessively long if low approach velocities are desired.

A second look at direct trajectories is suggested before any further analysis of gravity-assisted asteroid rendezvous missions is undertaken. Nonminimum-energy direct trajectories with minimized VHPs have not been generated. These trajectories might significantly improve payload for direct asteroid rendezvous missions without large increases in flight time.

Table 7.1 summarizes multiple-mission applications to the three types of asteroid missions considered. The applications are made, in general, for trajectory improvements rather than for scientific compatibility of objectives.

8. COMET RENDEZVOUS MISSIONS

An extensive study of comet missions was recently completed by Narin, Pierce, and Roberts (1965). The results show that spacecraft could spend up to 7 hours in the comet coma during intercept. However, investigation of the comet nucleus is extremely difficult if not impossible because of approach velocities (VHP), which average 15 km/sec. (A mission to the comet Kopff during the 1983 apparition had the lowest VHP, 8 km/sec). A rendezvous maneuver would provide long-period observations of the nucleus composition, temperature and

Table 7.1

MULTIPLE ASTEROID MISSION SUMMARY

Mission Type	Objective	Suggested Trajectory	Comments
Precursor asteroid belt fly-through	To test spacecraft design and assess asteroid collision hazard.	Earth-Mars-asteroid belt	Mars gravity assist increases the asteroid belt penetration
Asteroid belt fly-through	To determine mass and orbit distribution of asteroidal particles, investigate interaction processes, and return samples for chemical and structure analysis.	Earth-Jupiter-Earth	The flight path includes a close flyby of Jupiter and return to Earth in 2.8 years. Multiple target objectives are good.
Asteroid rendezvous	To observe surface features, measure temperature and magnetic fields, evaluate erosion effects, and conduct seismic and composition analysis with impacters.	Undecided	Direct minimum VHP trajectories have not been studied yet. Mars and Jupiter can reduce high VHPs for rendezvous, but trip times are long.

physical properties, but it is precluded by the high VHPs. Reduced comet VHPs should be possible with either direct trajectories unrestrained in ideal velocity and trip time or gravity-assisted trajectories.

Venus-, Mars-, and Jupiter-gravity-assisted trajectories were briefly analyzed. In order to intercept periodic comets with low VHPs, Venus- or Mars-assisted trajectories should have aphelia similar to the comets, i.e., > 5 AU, but such trajectories are also similar to Venus- and Mars-assisted Jupiter intercept trajectories. It has already been pointed out (Niehoff 1965) that direct trajectories are favored to these types of gravity assist.

Jupiter-assisted trajectories appear to be more useful. Low VHP trajectories that intercept the comet near aphelion (and Jupiter) are possible with Jupiter's gravity assist. The probability of achieving a close intercept, however, is extremely sensitive to an accurate determination of the comet's orbit. Such a determination is especially important since the comet orbit elements are going to change because of a natural gravity assist at or near the mission intercept time (the comet must also be near Jupiter at the time of the spacecraft gravity assist if VHPs are to be kept low). Unfortunately it is when the comets are near aphelion that their orbital elements are least well known. Until the secular perturbations of comet orbits between apparitions are better understood, Jupiter-assisted aphelion-rendezvous comet missions will not be practical.

Several special cases of gravity-assisted comet missions have been investigated. Direct trajectories to Halley's comet have extremely high VHPs of almost 70 km/sec, primarily due to the comet's retrograde motion. Analysis of Jupiter-assisted Halley trajectories revealed that the VHP could be reduced to 2 km/sec with the proper location of Jupiter in its orbit and a perihelion intercept. However, Jupiter's orbital position for the 1986 apparition is completely unsatisfactory for the required trajectory. Jupiter-assisted trajectories to Schwassmann-Wachmann I were also studied. This comet's orbit is nearly circular and lies slightly outside that of Jupiter. Post-Jupiter trajectories of more than 4 years are required to provide a tangential approach (low VHP) to the comet. The next launch period in the early 1970s seems premature. Similar opportunities will not reappear until about 2015.

Although first impressions of gravity-assisted comet rendezvous missions seems discouraging, their potential cannot be discounted. However, a study of unrestrained (nonminimum energy) direct trajectories should be considered for these rendezvous missions before the gravity-assist technique is further analyzed.

Gravity assist from Mars used as a midcourse maneuver for comet intercept missions has received some attention. At least two opportunities of this type that occur during the next 5 years have been found by Reese Jensen (1965): Schaumasse in 1968 and Encke in 1971. Energy requirements are low, possibly permitting an Atlas-Agena launch. Trip times are about

450 days. The 1971 Encke mission could be considered as a secondary objective of a 1971 Mars flyby mission.

9. PLANETARY SATELLITES

Planet orbiter missions should consider gravity assist from the satellites of the planet to be orbited for two reasons: (1) A satellite gravity assist may provide a method of capture without retropropulsion or aerodynamic braking, (2) orbital maneuvers might be possible from satellite assists which allow multisatellite exploration with one orbiter.

The application of this idea, if feasible, would require sophisticated guidance and good ephemerides of the satellites. Despite these problems, it seems worthwhile to present some indication of the gravity assist potential of the larger satellites of the solar system. An energy ratio was formulated such that:

$$\frac{\Delta E}{|E|} = \left[2\,\frac{R_s/R}{M_o/M_s}\right]^{1/2} \qquad (9.1)$$

where

R_s = the orbital radius of the satellite

R = radius of the satellite

$\frac{M_o}{M_s}$ = reciprocal mass ratio of satellite (s) to planet (o).

ΔE is the maximum energy change available from gravity assist (Niehoff 1965). $|E|$ is the absolute value of the energy of the satellite's orbit. Equation 9.1 applies to the planets of the solar system as well; i.e., they can be considered satellites of the Sun. In this way the energy ratio of a satellite could be compared with energy ratios for the planets to obtain a preliminary indication of its gravity-assist potential.

Energy ratios for a number of planets and some of their larger satellites are presented in Table 9.1; ratios greater than 1.0 represent gravity-assist capture or escape capability. The only satellite in this category is our moon. However, Ganymede and Callisto of Jupiter, Titan of Saturn, and Triton of Neptune would be useful for orbital maneuvers; for example, a maximum-energy gravity assist from Triton could change the aphelion of a Neptune orbit from 100 down to 20 Neptune radii. Ratios less than 0.25 indicate little or no gravity assist capability. Diemos of Mars and Io of Jupiter are in this category.

10. CONCLUSIONS AND RECOMMENDATIONS

Venus gravity assist for Mercury exploration is recommended. Payload improvement as well as several compatible objectives make Earth-Venus-Mercury missions useful. Very recent results indicate, however, that only the 1970 and 1973 launch opportunities can be used for this multiple mission between now and 1981. If Venus flyby missions are planned for 1970 and 1973, the inclusion of a Mercury flyby should be seriously considered.

All outer-planet flyby missions between 1976 and 1985 benefit from Jupiter or Saturn gravity assists. Common scientific objectives and much reduced flight time are the key

Table 9.1

COMPARISON OF GRAVITY ASSISTED ENERGY CHANGE OF PLANETS AND SATELLITES

Planet	Satellite	Reciprocal* Mass Ratio	Orbital Radius*, 10^3 km	Radius*, km	Energy Ratio ($\Delta E/\lvert E \rvert$)
Earth		328700	149600	6378	0.52
	Moon	81.33	384	1738	3.28
Mars		3089000	227940	3380	0.28
	Diemos	12910000**	9	6	0.02
Jupiter		1047.38	778300	71350	6.44
	Io	26000	422	1670	0.18
	Ganymede	12300	1070	2550	0.36
	Callisto	20000	1883	2360	0.38
Saturn		3497.6	1427000	60400	5.18
	Titan	4150	1222	2400	0.68
Uranus		22930	2869000	23800	4.58
	Titania	20000	438	500	0.40
Neptune		19100	4498000	22200	6.50
	Triton	750	353	2000	0.96

* Data from Allen (1963).

** Diemos mass = 5×10^{19} g.

advantages. A detailed study of the "Grand Tour" mission (1977 or 1978) is suggested since it is representative of all those considered. The study should focus on areas of experiment selection, overall spacecraft design and launch vehicle selection, launch window definition, planet encounter profiles, and guidance and control requirements. In view of the density of gravity-assisted outer planet opportunities in the late 1970s and the priority of other outer-planet investigations, a Jupiter-assisted Pluto mission is not suggested until 1989 or 1990. The use of gravity assist with outer-planet orbiter missions is not recommended due to the higher planet approach velocities which are generated.

Direct trajectories are suggested for low-latitude OOE missions. Venus- and Mars-gravity-assisted orbits are limited to a maximum inclination of about 15°. Jupiter assists, on the other hand, provide a wide variety of 90°-inclination orbits in the range of ideal velocities between 55,000 and 65,000 ft/sec. Additional objectives such as a solar probe, Earth flyby, and solar system escape are possible. Jupiter gravity-assisted trajectories are emphasized for OOE exploration.

Solar probe missions down to 0.1 AU should use single or multiple Venus assists to decrease energy requirements and to enhance mission objectives. Jupiter assists are recommended for probes to less than 0.1 AU. Flight times for Jupiter-assisted solar probe missions can be reduced to less than 2.5 years with ideal velocities on the order 57,000 ft/sec and miss distances within a Jupiter radius of Jupiter.

Reconnaissance missions are useful to unmanned exploration for large data return and recovery of collected asteroid samples. An Earth-Jupiter-Earth mission could be practical for both of these reasons.

Initial asteroid fly-through missions should use a Mars gravity assist to increase the belt penetration and to test spacecraft with a gravity-assist maneuver in preparation for later Jupiter-assisted outer-planet missions. The use of Mars or Jupiter assists for asteroid rendezvous missions cannot be properly evaluated until further analysis of nonminimum-energy direct trajectories is completed. This same conclusion applies to comet rendezvous missions.

These results and conclusions support continued interest in the application of multiple missions to solar system exploration. Although some additional effort in general gravity-assisted trajectory analysis is necessary, specific multiple mission studies based on the above conclusions should be initiated. In particular, compatible experiment selection and analysis of spacecraft design, launch window parameters, guidance requirements, and encounter profiles are needed. Jupiter-assisted missions are recommended as first priority since they have the largest potential for expanding solar system exploration.

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