Prospects for early manned interplanetary flights

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Mars and Venus beckon; many good trajectories present themselves during the early 1970's; and the need exists to reconnoiter these planets for possible propellant materials, as well as for scientific purposes

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This study of early interplanetary flyby and capture missions investigates gross requirements for such trips and determines the effects of variations in launch year, trip duration, propulsion systems, and entry modes on the performance of the missions. These evaluations are based on systematic searches through all trip possibilities of practical interest, using realistic trajectory information and subsystem constraints in keeping with the latest technological advances.[1-4]

Because of the complexity and cost of any planetary exploration program, it is imperative that exhaustive preliminary analyses be performed to define the scope and means for carrying out such an enterprise. The plan must take into consideration the requirements for a complete spectrum of mission choices in the time period of interest; the availability and capabilities of existing and projected space vehicles; and the necessary funding and scheduling operations, especially as they relate to the national lunar program and various other major efforts. Thorough preliminary analyses should, in addition, point the way toward the requirements for new and more capable designs, aimed at eventual execution of the most ambitious of the desired missions.

In the present study, certain assumptions have been made concerning subsystem development and human engineering requirements, in order to test their implications for total system design. Meaningful space mission planning is possible only if definite, albeit tentative, magnitudes are assigned to the many critical factors.

These assumptions are made with the authors' full realization that several may be subject to debate, that some of the physical problems which enter into the calculations still lack solution, and that fluctuations in economic and political climates make accurate predictions extremely difficult. Moreover, this study is not meant to be a final plan for planetary exploration, but rather a rational assessment of possibilities and alternatives for conducting the early phases of such a program. It is intended also as a point of departure from which further, more extensive studies of interplanetary travel can be undertaken. Some of the preliminary goals for these later studies are analyzed here and evaluated in the light of this plan for early space exploration.

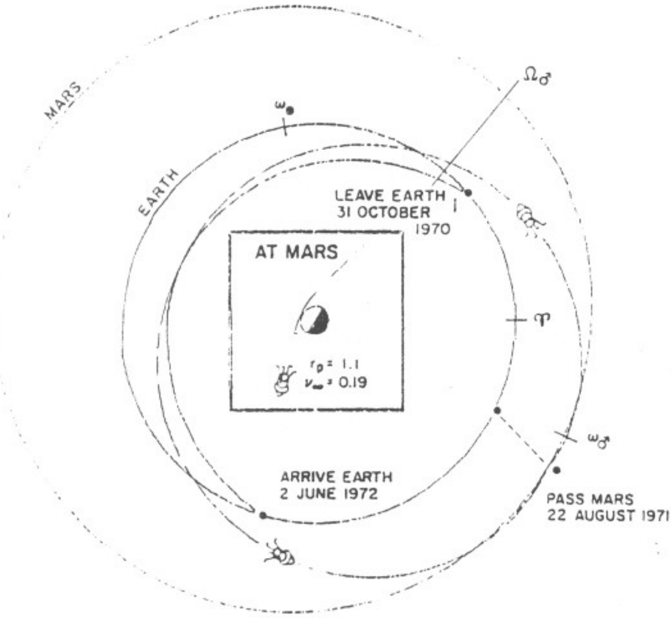
Prohibitive requirements for manned landings on the planets have made it necessary to confine this study of early missions to nonstop flyby trajectories or, at best, short orbiting planetary captures. During these early flights, however, it will be possible to conduct close preliminary reconnaissance operations, to check out subsystems and establish criteria for their use in later, more ambitious missions, and to define requirements and tolerance factors for the crews of future manned-landing missions. This early space exploration program is designed so that it will not place excessive strain on national space funding and development capabilities, particularly during the critical period of 1963–75.

Various assumptions and alternatives have been employed in analyzing the missions. In some, both "safe" and relatively sophisticated assumptions are employed in parallel computations, in order to bracket the system requirements within the extremes dictated by these alternative choices. It is important to note that the selection of orbits has not been performed on the basis of minimum characteristic velocity or even on minimum weighted velocity sum, but rather by completely evaluating each trip of interest, allowing for estimated values of life-support subsystems, inert-weight fractions, re-entry-system weights, and other quantities of importance, as they pertain to each individual case.

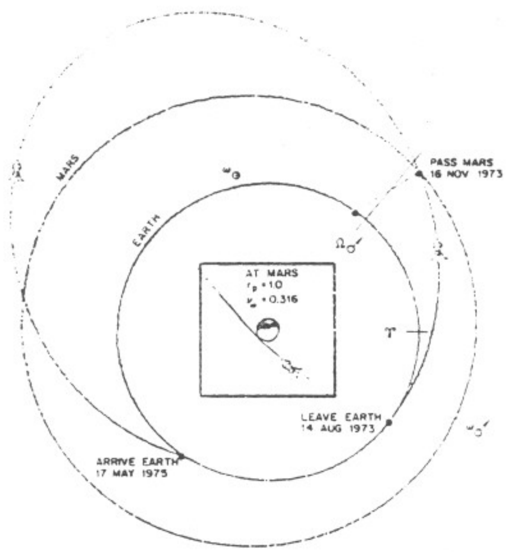
Because of the underlying mission philosophy, it was felt appropriate to assume a level of technological accomplishment of the advanced Apollo period. Crew size was limited to three men, in keeping with this restriction. Earth-escape systems considered included both the chemical (O_2/H_2) and early nuclear types, and entry was assumed to be effected either by solid-propellant retro propulsion down to parabolic speed or by an advanced atmospheric braking technique, which, in addition, would employ a small auxiliary rocket to provide negative lift for the maintenance of proper entry-corridor height. Advanced ablator designs are also under study, but it is unlikely that they will result in major weight revisions, even if they do prove to be ultimately preferable to the other two entry concepts. Planetary escape, during the capture missions, has been calculated for a storable chemical rocket of moderate impulse rating.

A semiclosed-cycle life-support system, in which liquid but not solid metabolic waste is reprocessed, was tentatively selected, and a variable life-support allotment of 22.7 lb/day, plus 3500 lb of fixed weight, was adopted for the three-man crew. Radiation shielding of 50–55 gm/cm^2 was assumed as a measure to restrict solar-flare dosage to a level where the probability of absorbing more than 200 rads to the blood-forming organs dur-

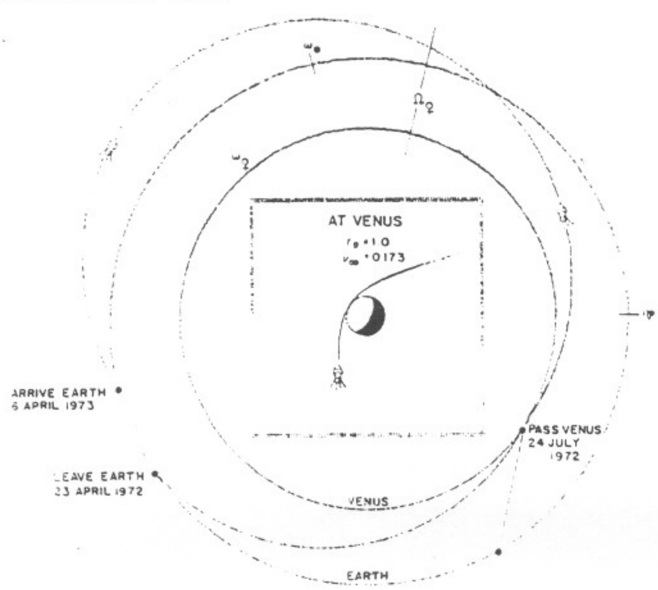
HIGH-ENERGY NONSTOP FLYBY PAST MARS



LOW-ENERGY NONSTOP FLYBY PAST MARS



NONSTOP FLYBY PAST VENUS



ing an assumed statistical distribution of major and minor solar flares is held to 0.0001. Midcourse propulsion of 2000 fps to the heliocentric payload was taken for the flyby trajectories, while a 3000 fps capability was allotted for the capture missions. Both values appear to be quite conservative. A lump sum of 10,000 lb (flyby) or 5000 lb (capture) has been devoted to the scientific payload, which would probably include one or several sounding probes to be released during planetary contact.

Finally, the crew's quarters were assumed to be centered in a 20,000-lb mission module and a 9000-lb modified Apollo command module, the latter also serving as the Earth-re-entry vehicle.

The table on page 19 summarizes these considerations.

The flyby missions investigated utilize realistic, joined-conic trajectory data,[1] which include the effects of terminal planetary perturbations, orbital eccentricities, and inclinations. Two types of Mars flyby trips were considered, high energy and low energy, with the high-energy group further qualified into darkside and lightside passages. In the darkside passage, the planet lies primarily between the vehicle and the Sun at the time of closest passage. Although the darkside, high-energy passages offer poor visual contact at the most crucial point in the flyby trip, they are, nevertheless, much less demanding on both vehicle mass and total trip time, when compared with the corresponding lightside-pass trips. Any final choice between these two approaches however, must naturally be deferred pending more definitive resolution of the mission objectives for each trip, as well as the time history of surface visibility during each particular passage.

The top two charts display sample mission profiles from the high-energy and low-energy Mars-trip categories. The high-energy group of trajectories all dip within the Earth's orbit and perform about 1-1/2 solar circuits during each complete trip. In the region of interest, these arcs generally reach perihelion distances comparable with Venus' orbital radius and aphelion distances barely touching Mars' orbit. In this latter statement lies the explanation for large yearly variations to be observed in the high-energy mass requirements. For, when equivalent trips are compared during different opposition periods, these near-aphelion contacts will occur at different radial distances from the Sun, due to Mars' appreciable orbit eccentricity. This variation in distance at contact is reflected in corresponding wide fluctuations in launch mass.

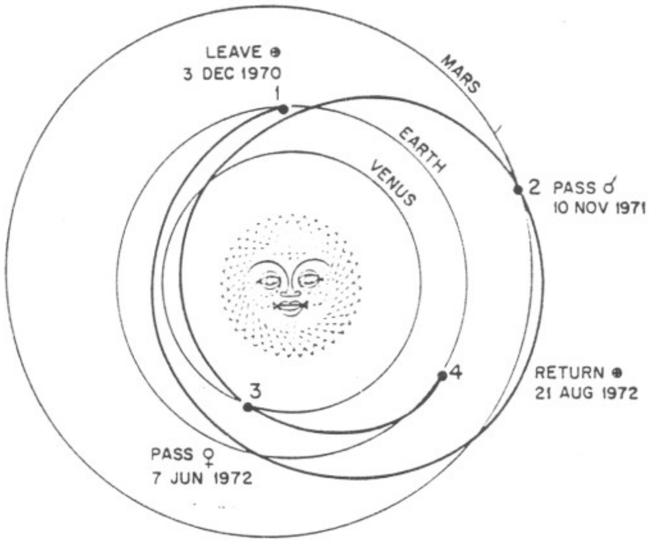
The low-energy trips never pass inside the Earth's orbit. Because of this, they may possibly possess advantages in terms of shielding requirements against solar flares, although we need much more knowledge here. Because of the attendant great aphelion distances, however, larger solar collector sizes and new temperature-control techniques are expected to be required for this group of trips. Speeds of passage at Mars are relatively high, but not prohibitively so. Planetary contact does not occur near aphelion for these trips, and the terminal speed (and mass) requirements are therefore considerably more stable than for the high-energy missions. All trips involve "twilight" passages, for which the point of closest approach lies near the terminator.

The low orbital eccentricities of Venus and Earth assure that the requirements for trips between these two planets will not suffer sharp yearly variations, as for Mars missions. Moreover, since few trips of interest possess legs which travel through angles of about 180 deg, we can be assured that orbital inclination effects will be negligible in Earth-Venus trips. The Venus missions are very attractive, for the planet's rather large mass can be used to advantage in deflecting a nominally unacceptable trajectory into an attractive round trip. In this way, desirable missions can be selected which leave at speeds near the Hohmann value, return also at modest speeds, and require not more than about a year for execution. The third chart on page 17 shows a representative trajectory from this group.

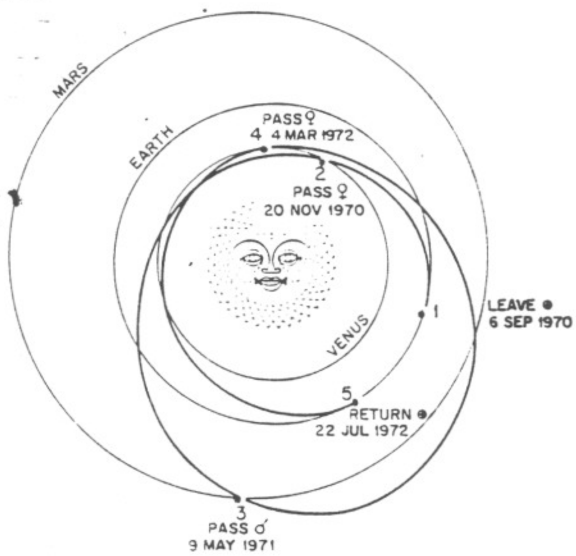
All missions considered in this study involve close-approach distances of one planetary radius, that is, grazing passages. For some groups of trips, modest savings may sometimes be realized by passing at a greater distance, but present system uncertainties make more precise analysis of these effects unwarranted at this time.

An unusual type of flyby mission, possessing significant potential for planetary reconnaissance, is the multi-planet flyby, or "interplanetary grand tour." Two promising grand tours are displayed in the two charts at top. Although these are repetitive in a phenomenological sense every 2338 days, the mission requirements are not strictly repetitive owing to the eccentricity of Mars' orbit. Of the three special trips presented, the first yields less total trip time than any reasonable trajectory which passes Mars only; the second passes both planets on their lighted sides but requires less mass than any available

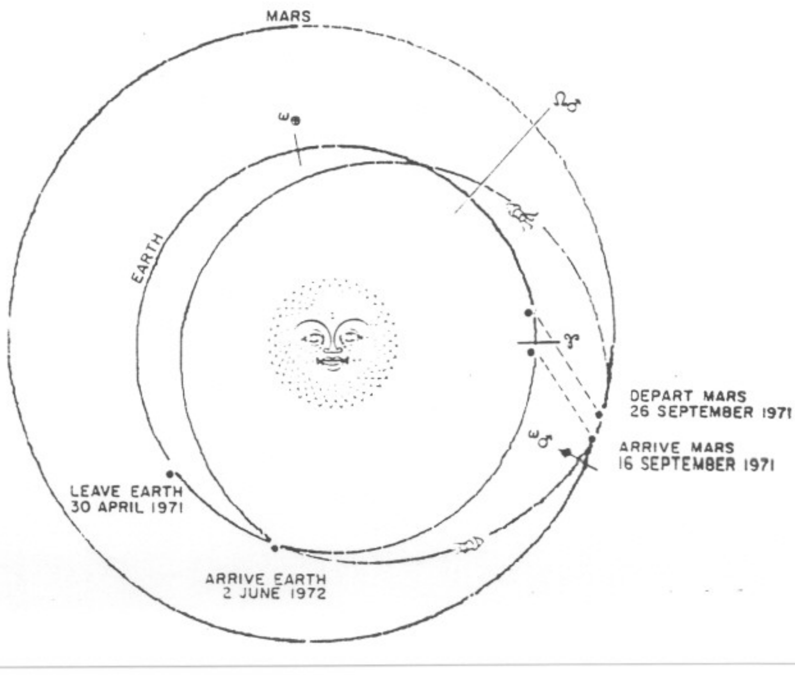
TWO-PLANET FLYBY IN 1970–72



THREE-PLANET FLYBY IN 1970–72



MARS CAPTURE MISSION WITH 10-DAY STOPOVER



lightside passage of Mars alone; and the third trip passes Venus, Mars, and Venus again with launch and recovery velocity requirements which are less than those for any other trip considered, including those for the Venus flybys.

The important point is that both planets may be reconnoitered for essentially the same requirements as for the single Mars nonstop trip. This means that the amount of information obtainable per trip is greatly increased, and little or no penalty is incurred in launch weight. Guidance problems associated with these journeys do not presently appear to be insuperable, although a major disadvantage of the trips stems from their restricted launch windows and long repetition cycle. If they are not performed at the times indicated, the next opportunities for such easy missions will not present themselves for an additional 13 years.

In the study of capture missions, a 10-day orbiting stopover was assumed. Although this value was selected somewhat arbitrarily, it was felt that a substantially shorter stay time would only serve to nullify the great expense involved in establishing and leaving the capture orbit, while any appreciably longer capture would increase the speed requirements unduly. In each opposition period considered, all trips possessing some constant total mission duration were studied, and a trajectory was located which yielded minimum mass on parking orbit, for the particular subsystem concepts selected. With this point located, the next value of total duration was selected and process repeated. Thus it was possible to locate a mass/time curve in which each point represented minimum mass for that trip time.

The Mars-capture with 10-day stopover shown at the bottom of page 18 represents a very attractive mission from the 1971 group of stopover trips, which employ a chemical escape system together with a solid-propellant retro-motor for Earth approach. This profile is fairly typical of all promising stopover trips, regardless of the year or system selected, although the actual speed and mass requirements usually vary markedly from mission to mission.

The graphs shown on page 20 present the principal results from the mission analyses. The flyby mission summaries on page 20 compare system performance requirements for the years 1970–75, using four different transportation system variants: Chemical escape/retro-rocket re-entry; Chemical escape/aerodynamic braking; nuclear escape/retro-rocket re-entry; and nuclear escape/aerodynamic braking.

All four flyby graphs display mass required on Earth parking orbit plotted against mission duration. Since the various groups of trips seem to separate into individual clusters, it was possible to plot all flyby trips together on each graph. For every group of trips, the yearly variations in mass requirements produced a natural "stacking" of curves within each category.

The left-most set of curves for each flyby graph portrays mass requirements for Venus missions in the 1970, 1972, and 1974 time periods. These lines show little yearly variation, and it appears that a capability for performing such missions during any particular period could also be applied to this task during any other period. Owing to the flatness of these curves, we might expect to reduce trip times by perhaps four to six weeks beyond the values corresponding to the minima without suffering undue increases in system mass.

SYSTEM-DESIGN ASSUMPTIONS

Subsystem	Flyby Missions	Orbital Stopovers
Crew	Three men	Three men
Earth entry	Solid-propellant retrorocket brake Aerodynamic braking with lift control	Aerodynamic braking with lift control
Life support (three men)	Semiclosed system = 22.7 × trip time + 3500 lb	Semiclosed system = 22.7 × trip time + 3500 lb
Radiation shielding	Storm cellar, 50 to 55 gm/cm^2 (0.0001 probability of 200 rads to blood-forming organs)	Storm cellar, 50 to 55 gm/cm^2 (0.0001 probability of 200 rads to blood-forming organs
Power supply	Solar boiler or Snap-8 type	Solar boiler or Snap-8 type
Command module	Modified Apollo with re-entry system	Modified Apollo with re-entry system
Midcourse correction	2000 fps to heliocentric payload	3000 fps to heliocentric payload
Probes and scientific equipment	10,000 lb	5000 lb
Earth escape	Chemical (430 Isp); nuclear (830 Isp)	Chemical (430 Isp); nuclear (830 Isp)
Capture at planet	—	Aerodynamic braking with lift control
Planetary escape	—	Storable chemical (330 Isp)

Darkside, high-energy Mars flybys are shown in the next set of stacked curves in the flyby graphs. These, as well as the corresponding lightside flybys to their right, are characterized by sharp minima and wide yearly variations in minimum mass requirement. These trips seem useless beyond 1973, since the required expenditure in subsequent years can more profitably be applied to performing capture missions. In comparing both high-energy groups, the darkside passages show marked superiority in mission requirement as well as trip time, although suffering in regard to planetary visibility during passage.

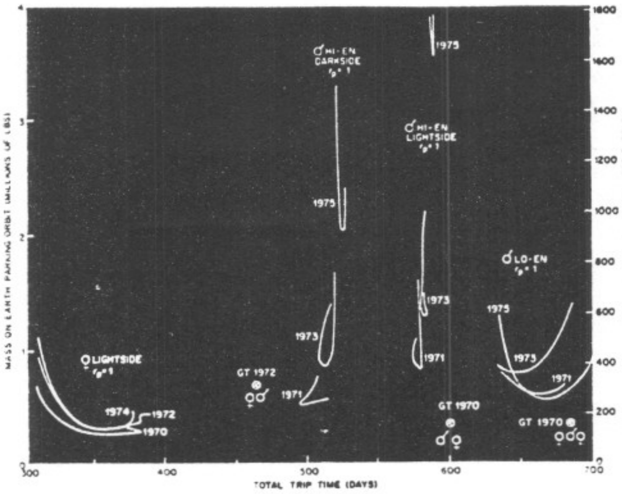
Lower mass requirement beyond 1971 for the low-energy trips (the right-most group in the flyby graphs) appears to afford ample compensation for the additional 100 to 200 days of travel time involved in these missions. Whether to spend 18 or 22 months on a Mars journey seems a secondary issue in comparison with the stringent mass requirements for the shorter missions during later time periods.

Advantages of the three Grand Tour journeys (labeled "GT") are obvious, as are their disadvantages, which were mentioned previously. The 1970 trip passes Mars' illuminated side only 98 days after opposition and Venus' illuminated side only 11 days before conjunction—a doubly remarkable mission, since the requirements are of the same order as for the simplest Venus journeys. The 1972 Grand Tour suffers by requiring large communication distance during the Venus passage, but otherwise appears quite acceptable. Selection of the three-planet flyby in 1970 will reward the analyst with an incomparable opportunity for two good observations of Venus, each near the times of inferior conjunction, and a good view of Mars, also near opposition. Speeds at both ends of this trip are comparable to Hohmann values for missions to Venus.

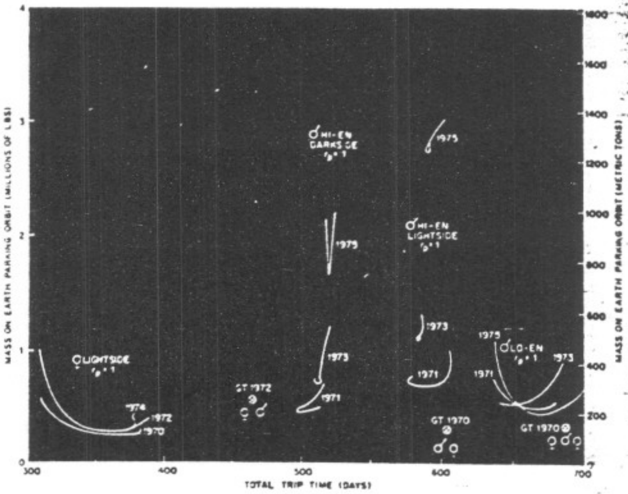
The reader may compare for himself the weight reductions which accompany the introduction of nuclear escape propulsion and aerodynamic re-entry. Savings due to the introduction of the sophisticated re-entry system become more dramatic for the later Mars missions, which involve considerably higher approach speeds and which could, consequently, exploit this technique to its fullest advantage.

Aside from the obvious advantage of requiring lower vehicle mass for a given trip, the nuclear escape system

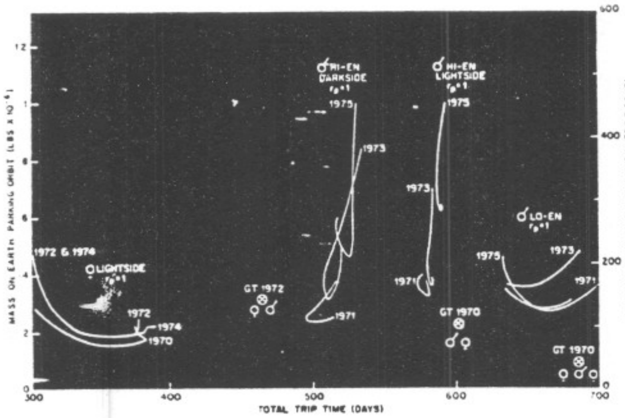
FLYBY MISSION REQUIREMENTS FOR VARIOUS YEARS



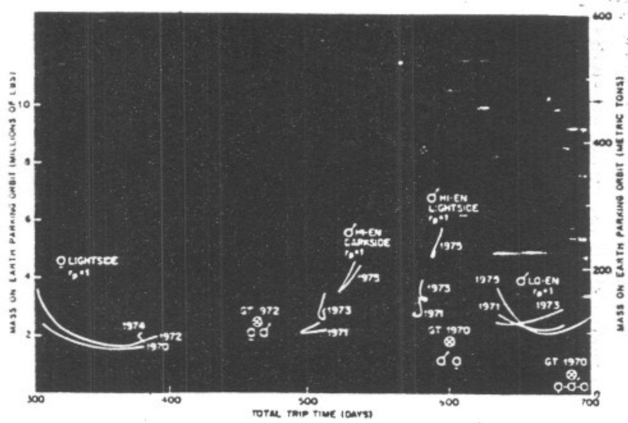
A. Chemical escape—retro Earth entry.



B. Chemical escape—drag-brake Earth entry.



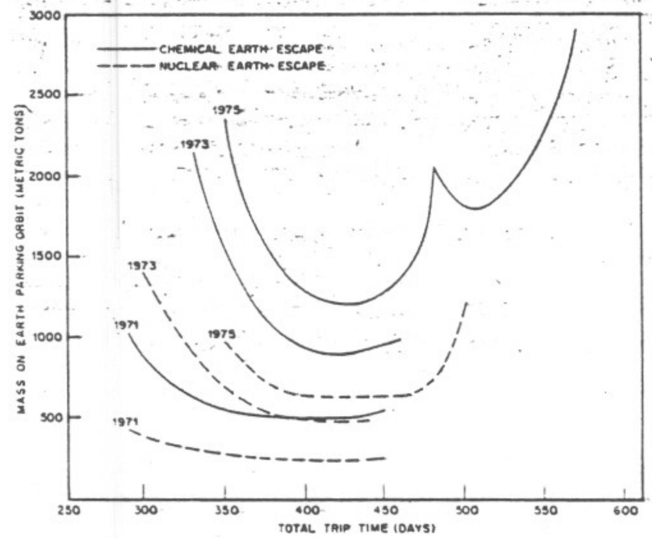
C. Nuclear escape—retro Earth entry.



D. Nuclear escape—drag-brake Earth entry.

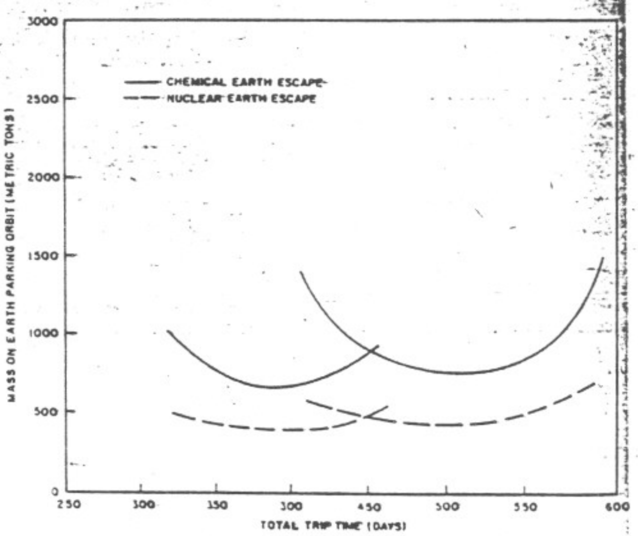
MISSION REQUIREMENTS FOR VARIOUS OPPOSITIONS

Mars 10-Day Stopover: Drag-Brake Earth Entry



MISSION REQUIREMENTS FOR 1972 CONJUNCTION

Venus 10-Day Stopover: Drag-Brake Earth Entry



allows, in addition, greater variations in the selection of total trip time. Mass-requirement sensitivity is lessened by use of this type of escape stage, since its high specific impulse gives greater tolerance to higher incremental velocities without admitting inordinate increases in mass ratio. A strong example of this is depicted for the 1970 Venus flyby. By lowering the total trip time from 380 to 325 days, a saving of almost two months, the mass requirement increases by only 18%. In contrast, the same decrease in trip time using the chemical system results in a 38% increase in mass.

Bottom left graph on page 20 shows requirements for the 10-day orbiting capture missions at Mars in 1971, 1973, and 1975. In each of the three periods, two groups of trajectories showed promise for worthwhile missions: (1) Outbound leg transfer of less than 180 deg/return leg of more than 180 deg; and (2) Outbound leg transfer of more than 180 deg/return leg of more than 180 deg. Results from both areas are shown for the 1975 trips. It should be noted, however, that this division into two groups is a somewhat artificial one, owing to the presence of 180-deg transfer ridges in the orbital transfer analysis. Application of a major midcourse propulsion maneuver to "break" the transfer plane will cause these two areas to merge smoothly.[5] Nevertheless, the former of the regions is still favorable because of the lower required system mass and the considerably shorter mission times. A complete analysis of the three opposition years indicates that this selection is valid although the differences in mass are not quite as significant. Consequently, the curves shown for 1971 and 1973 have been restricted to these areas of relatively short trip duration.

Although the reader may object to some or all of the assumptions applied in the present study, it is clear that any set of self-consistent calculations maintains validity in a relative sense, if not in an absolute one. That is, even though the mass levels quoted in the summary figures might be somewhat in error due to questionable assumptions, nevertheless the percentage increases and sharpness of curvature of the minimal solutions should still prove valid under any other set of analogous constraints.

This being so, we may draw the following conclusions from the data.

1. If a capability exists for performing Venus flyby missions during any one calendar period, then we should be able to plan such missions during any other period. Trips of perhaps as low as 300 days duration should be feasible, without significant increases in system mass.

2. The scheduling of relatively short, high-energy flybys past Mars becomes impractical beyond 1973. Favorable opportunities for such trips do not reoccur until after 1983.

3. Low-energy Mars trips of somewhat longer duration (that is, about 630 to 680 days) appear to be feasible during any opposition period, although this group does exhibit some limited degree of yearly fluctuation.

4. A limited number of attractive multi-legged planetary flybys are available in the 1970–72 period. Considering the expense and complexity of scheduling any interplanetary manned mission, these trips seem to offer promising possibilities indeed for returning maximum dividends on any technological investment. Although launch windows are rather restricted and timing problems severe, such favorable mission opportunities will not occur again until after 1983.

5. Orbiting capture missions are more difficult than the flybys in terms of both required mass and complexity. The Venus trip curves again display a high degree of stability with regard to conjunction period, although the Mars missions begin to pay dearly for program delays beyond 1973; this situation will not improve until after 1983.

If, in addition, the various assumptions and weight factors adopted in this study prove to be reasonably accurate, then we can look forward to a hopeful prospect of performing the Venus flyby mission using a single Saturn V booster coupled with an early man-rated nuclear escape stage. Although it is far too soon to speak with any degree of certainty, even the prospect of performing this mission with a chemical escape stage appears to be reasonable. These possibilities, however, must await further definition of the tolerances and requirements for the many systems to be utilized.

Most of the missions described here must, of course, depend on either orbital assembly and/or available booster capability beyond the Saturn V level for successful performance. Of these two possibilities, the former seems a more likely prospect at this time. With orbital rendezvous, however, a point is ultimately reached beyond which it becomes economically unfeasible to assemble larger vehicles. This point is governed by many factors, including booster unit cost, logistics, reliability of on-orbit assembly, and so forth. Thus, the temporary relief in time gained by the delay of certain missions for several years may be completely offset by the enormous expense involved in performing these trips at the later date.

Forfeiture of the chance for early interplanetary launchings does not, of course, eliminate the possibility and opportunity of sending men to Mars after 1975. It does, however, call for a different approach to the total program. If water or some other potential propellant material were discovered on the planets themselves, direct surface landings and vehicle refueling would probably become the most economical method of performing most space missions. Study shows that this mode of operation could permit reductions of up to 70% in the launch mass for trips to Mars and up to 95% for Venus missions. Of course, even if this is to be the eventual plan, it would still be desirable to exploit the low requirements for early missions to search, from orbit, for refueling sites on the planets' surfaces and perhaps to land fuel-processing equipment and emergency provisions automatically for use by personnel on the later flights.

If propellant sources are not found on the planets, the effort for future flights must be directed toward developing very large vehicles and very powerful engines. This point alone dictates that the search for propellant should occupy a prominent place in the list of objectives for early flights, and that any comprehensive plan for interplanetary exploration should include this search before establishing performance specifications for future systems.

Acknowledgments

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