# GRAVITY THRUST AND INTERPLANETARY TRANSPORTATION NETWORKS *

Michael Minovitch**

This paper concerns a proposal for an Interplanetary Transportation Network which could provide an economical means of transferring large numbers of people from one planet to another. It could be used an indefinite number of times and would have no theoretical limit to its useful life expectancy. The network would involve several dozen vehicles all moving simultaneously on different planetary fly-by trajectories. Each trajectory profile can be represented by a series $P_0 - P_1 - P_2 - \dots - P_n$ where $P_0$ is the launch planet ( i.e., the Earth ) and where $P_i$ is the i'th planet encountered along the trajectory $(i = 1, 2, \dots, n)$. The integer n can be arbitrarily large. The energy required to change each leg of the profile at $P_i$ so that the vehicle will encounter $P_i + 1$ is obtained by utilizing the gravitational interaction between the vehicle and each successive planet. Therefore, after its initial injection from $P_0$, each vehicle remains essentially in a free-fall state and requires no additional on-board rocket propulsion. Hence, by choosing a very low energy initial transfer with a possible gravitational assist from the moon, it is theoretically possible to send massive vehicles on long-lasting interplanetary journeys which would take them past every planet in the Solar System an arbitrary number of times.

The purpose of this paper is to focus attention on such a network and to describe its practical potentialities. A thorough treatment requires a detailed numerical study far beyond what is presented here since there is a large number of potentially useful profile possibilities. I have included a list of references which may offer interesting reading.

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**Senior Research Engineer, California Institute of Technology, Jet Propulsion Laboratory

## INTRODUCTION

Our technology has advanced to the point where projects considered fantastic just a few decades ago will soon become realities. In the very near future, man will make his first journey from this planet to the surface of the moon. Realistic plans are already being made for the exploration of other planets. The end result of this effort to explore the vast distances of the solar system will be the development of interplanetary transportation networks which will enable ordinary people to make trips from one celestial body to another on a scale adequate for colonization. Let us consider some of the basic requirements of such a system. First, it will require ships of tremendous mass, capable of supporting hundreds of people in complete safety and comfort for many months. These gigantic space liners will be analogous in concept (if not in actual mass) to the largest, most luxurious ocean liners. They will be so expensive that the system must include dependable means of vehicle recovery. The networks will have to be highly efficient so that trip costs will be within reach of ordinary people.

Unfortunately, in our present state of understanding natural physical laws, we cannot construct transportation networks including all the planets. However, if one restricts the system to Earth, Venus and Mars, a network could be designed which would not require technological breakthroughs beyond those which can be reasonably predicted at this time. If flight times on the order of two or three years are acceptable, the network could probably be extended to include the moons of Jupiter and Saturn, although a definite answer to this possibility will require a more extensive numerical investigation than has been undertaken at this writing. In this paper, I will envision such an interplanetary transportation network and describe the concept of Gravity Thrust which will make it possible.

## INTERPLANETARY TRANSPORTATION NETWORKS

### The Initial Mass Problem

Many branches of modern technology depend upon a few key mathematical equations. One important equation in the field of rocketry and space flight is called the "mass ratio equation" (1) or "rocket equation",

$$m_1/m_0 = \exp(-\Delta V/c) \qquad (1)$$

In this equation $m_0$ and $m_1$ refer to a rocket's total mass before and after burning its engine to achieve a velocity increment of magnitude $\Delta V$. The rocket's exhaust velocity is denoted by c. When c becomes greater than some sufficiently large number depending on $\Delta V$, further increases will cause the mass ratio $m_1/m_0$ to approach unity very rapidly. This, of course, results in greater rocket efficiency. For this reason, it is important to design rocket engines which will generate the highest possible exhaust velocities. There are, however, certain upper limits for c which cannot be exceeded at present without basic engineering breakthroughs. For example, it is thermodynamically impossible to construct an ordinary chemical rocket engine which will generate an exhaust velocity greater than 4.4 km/sec. By employing nuclear propulsion, this figure can be doubled, but any substantial increase beyond this will be exceedingly difficult to achieve, Although it is theoretically possible to develop advanced nuclear propulsion engines which would have exhaust velocities greater than 10 km/sec, basic problems in fields such as metallurgy will have to be solved first. It is difficult, therefore, to speculate when these powerful engines will become available.

In view of the above facts, the implications of the mass ratio equation are quite striking and clearly demonstrate the great technological challenges which lie ahead. For example, some studies[1] have shown that in order to carry out a modest, one year, round trip, five-man landing expedition to Mars using presently envisioned nuclear rocket propulsion, it would be necessary to begin the mission with two 450,000 kgm vehicles already in orbit. The cost and difficulty involved in placing this tremendous mass in orbit will be enormous. If more massive payloads are contemplated, the problems become staggering due to the multiplying effects of additional fuel requirements.

Although the development of more powerful rocket engines will always play a leading role in our space program, I do not believe such engines can be a final solution to the initial mass problem. Most of the 900,000 kgm of required initial orbital mass in the above example is fuel. This indicates that the crux of the problem is the rocket engine itself. Since all rocket engines operate on the reaction principle, they derive their thrust by expelling mass. But with definite limits imposed on exhaust velocities, one is forced to carry greater fuel loads if greater payloads are required. Hence the cost and difficulty of a mission requiring both massive payloads and high $\Delta V$'s will be enormous. To obtain a more vivid picture of the tremendous launch vehicles and initial orbital masses required on various interplanetary missions using rocket propulsion, the interested reader should refer to reference 2. A more technical study involving interplanetary trajectories can be found in reference 3. This reference also contains excellent examples illustrating the process of calculating required initial masses.

## Gravity Thrust

In 1961 I proposed a method[4] for designing free-fall interplanetary trajectories which, after extensive numerical calculations, has proved to be a partial solution to the initial mass problem. This design technique treats planetary gravitational fields as powerful vehicle thrust sources which can be utilized in almost the same way as the thrust of an on-board rocket engine. These forces are controlled by very precise guidance of the vehicle's planetary approach trajectory. The most important advantage of this technique is that unlike the thrust provided by any on-board rocket engine, these thrust forces increase automatically with vehicle mass as described by the equivalence principle. This concept of vehicle propulsion, which I call "Gravity Thrust," combines the basic advantages of both the ion engine and nuclear engine in that it burns very little fuel (in fact, none at all) and can provide very high thrust forces. The Gravity Thrust acting on a relatively low mass 10,000 kgm vehicle as it passes within 10,000 km of the earth's surface will be tens of thousands of times more powerful than the largest ion engine ever constructed, and can maintain these high thrust levels (almost comparable to those of a high thrust nuclear engine) for several hours.

Since these Gravity Thrust forces are controlled by guiding the vehicle's approach trajectory, the "gravity engine" can be thought of as a small, accurate planetary approach guidance system. It s total mass can be about 2 to 5% of the vehicle's total mass and, depending upon it s accuracy, it can be designed for many successive planetary encounters.

To illustrate how the concept of Gravity Thrust may be applied to trajectory design, I will consider a simple hypothetical problem. Suppose a mission calls for a certain payload to be sent from planet A to some destination B, and that the time it arrives at B is not specified. (We shall not consider any possible thrusting maneuvers which may be required at B). Since Gravity Thrust is the result of an interaction between the vehicle and the gravitational field from some mass body, it s application will almost always involve re-routing the direct flight trajectory A-B to one which passes various intermediate planets before reaching B. The new profile can be expressed as $A-P_2-P_3-\ldots-P_{n-1}-B$ where $P_2$, $P_3$, ..., $P_{n-1}$ are n-2 intermediate planets or mass fields which will provide the necessary Gravity Thrust. The manner in which these intermediate planets are selected and inserted into the sequence is very important. The purpose, of course, is to enable the vehicle to reach B by using less energy than would be required for a direct transfer A-B. After the initial $\Delta V$ is imparted to the vehicle to send it to $P_2$, all other thrust forces are supplied "free-of-charge" by gravity. Consequently, it will not matter if, after injection, the vehicle's mass is 100 kgm or 100 million kgm. Of course in some cases more energy may be required to reach B via intermediate planets than to reach B directly. In this case the $P_i$'s can be thought of as possible moons moving in the vicinity of A. In the event there are no such moons or that utilizing their mass fields imposes too many trajectory constraints compared with total benefits, the mission may proceed on a direct flight profile.

When I first proposed that interplanetary trajectory design should be based upon the vehicle's gravitational interaction with intermediate planets, there was skepticism as to whether the technique would be practicable, given the planetary orbital and mass characteristics of our particular solar system. This doubt was removed when preliminary calculations at JPL showed that even a relatively low mass planet like Venus possessed the gravitational capability of radically changing a free-fall trajectory about the Sun after a sufficiently close encounter. A full scale numerical investigation began in February 1962 at the UCLA computing facility[5] with the aid of a large IBM 7090 digital computer. The results of this early research at UCLA and, later, at JPL, clearly pointed to the potential importance of the Gravity Thrust concept for all types of interplanetary missions, both manned and unmanned.

Since it is not my purpose to report on specific missions affected by Gravity Thrust, I refer the reader to references 6 through 14 for this information. But in order not to leave the reader totally dependent upon references, I shall present a few numerical examples illustrating the practical applications of Gravity Thrust. In these examples the following notation will be used:

$\Delta V$= magnitude of velocity increase required for injection from Earth parking orbit (km/sec). The Earth parking orbit is assumed to be circular and 200 km high.

HEV= hyperbolic excess velocity (km/sec)

T= flight time between encounters (days)

$\Theta$= heliocentric transfer angle swept out about the sun between encounters (degrees)

a= semi-major axis of interplanetary transfer trajectory between encounters (A. U.)

e= eccentricity of interplanetary transfer trajectory between encounters

DOCA= distance of closest approach to a planet's surface during an encounter (km)

TISI= time in gravitational sphere of influence[12] (days)

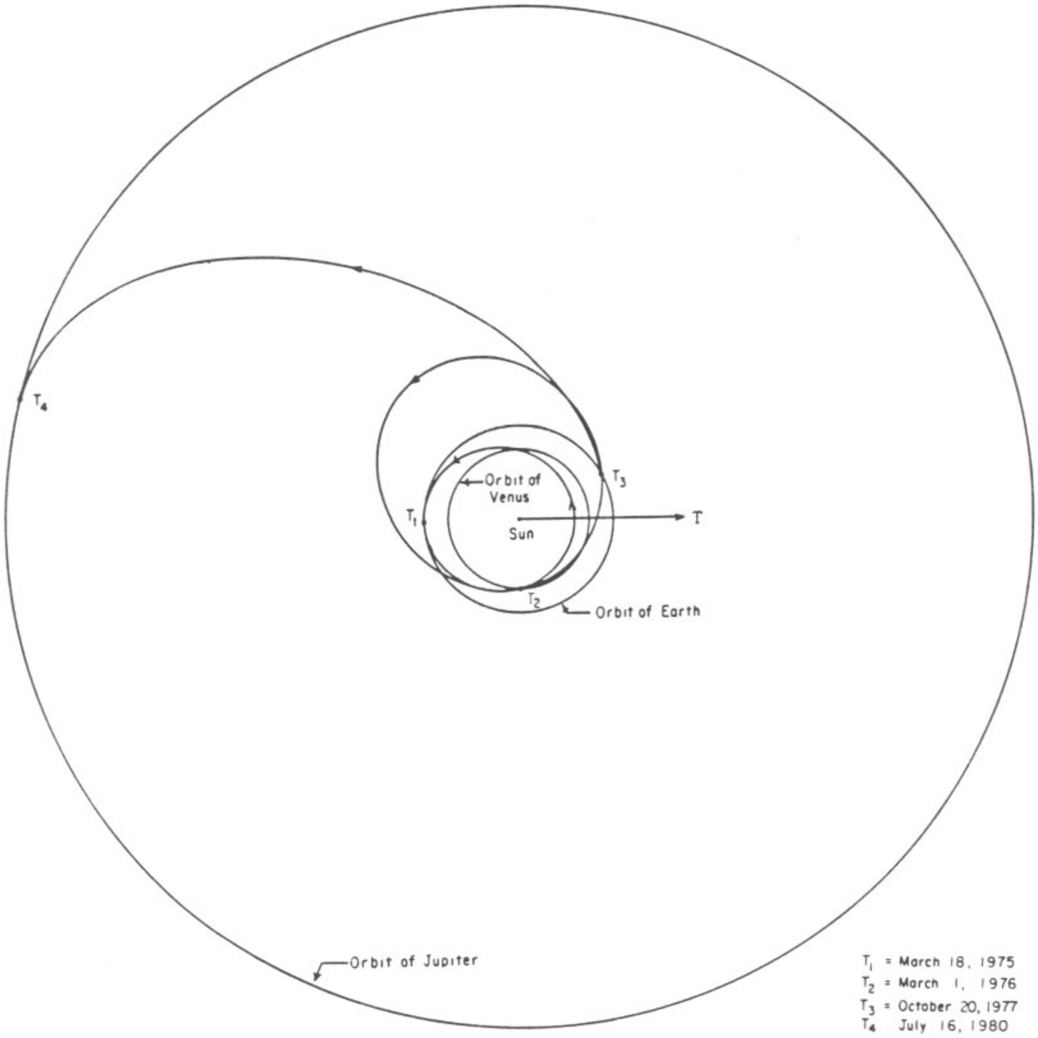
DA= deflection angle of vehicle's velocity vector relative to the encountered mass body due to Gravity Thrust.

TDA= total deflection angle of vehicle's velocity vector relative to the Sun due to Gravity Thrust from an intermediate mass body.

IMPV= magnitude of vehicle's velocity change due to Gravity Thrust.

The three examples below will demonstrate how Gravity Thrust can enable a vehicle to leave the Earth and encounter the planet Jupiter with extremely low injection energies. To compare these Gravity Thrust trajectories with ordinary direct flight transfers, let us recall for a moment some characteristics of ordinary Earth-Jupiter trajectories. The so called Hohmann or minimum energy direct flight trajectories to Jupiter require injection $\Delta V$'s of about 6.62 km/sec (HEV= 9.30 km/sec). The flight times are about 2.5 years. By increasing $\Delta V$ to 7.78 km/sec (HEV= 11.00 km/sec) this flight time can be reduced to about 1.4 years. The most powerful oxygen-hydrogen chemical rocket engine having an exhaust velocity of 4.2 km/sec will require vehicle mass ratios of .21 and .16 for the above injection velocities. This means that in order to send a 4,500 kgm payload to Jupiter, an initial mass of at least 21,500 kgm will be required.

The first example (see figure 1) illustrates a profile of the form Earth-Venus-Earth-Jupiter. Some of its important trajectory characteristics are listed in Table 1. The fact that this trajectory comes closer to the center of the Earth than the planet's own radius is of no serious concern in this paper. A surface penetration of 400 km is only about 1/16 of the Earth's radius. This closer approach distance can be raised by introducing a slight velocity maneuver on the approach asymptote or by choosing a slightly different launch date $T_1$ and first planetary encounter

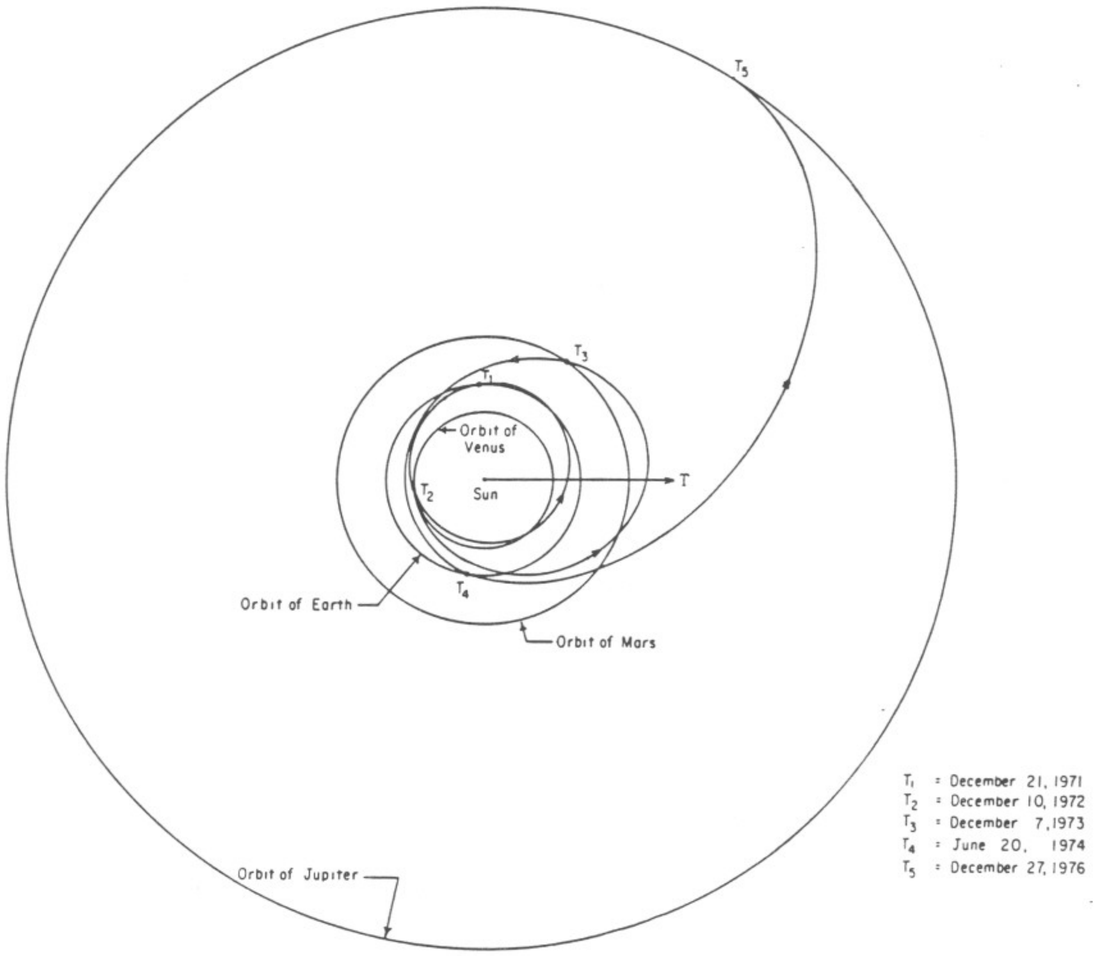


T1 = March 18, 1975
T2 = March 1, 1976
T3 = October 20, 1977
T4 July 16, 1980

Fig. 1 Earth - Venus - Earth - Jupiter

date $T_2$ (although this second alternative will probably require a slightly higher initial $\Delta V$). The total flight time is approximately 5.3 years but the injection velocity $\Delta V$ is only 4.06 km/sec. Consequently, if the oxygen-hydrogen chemical rocket engine with an exhaust velocity of 4.2 km/sec mentioned above is used, the initial mass ratio increases to .39. Hence with the same 21,500 kgm the payload can be increased to 8,400 kgm -- a payload about 85% greater than the direct flight payload. It should be noted that both the Earth-Venus and the Venus-Earth legs of this trajectory are Type 3 (i.e., $360^\circ < \Theta < 540^\circ$). Thus one should be able to find profiles of this form with nearly the same geometric aspects but with at least one of the transfer angles less than 180° (i.e., Type 1). If such a value were found for the Earth-Venus leg, the total flight time would drop to 4.5 years. With such a reduction in the Earth-Venus leg, the flight time would drop to only 3.9 years -- about as long as the flight time of the direct flight minimum energy Type 2 trajectories. If both legs were Type 1, the total flight time would be only 3.2 years. This, however, would be a rare occurrance. Round trips to Venus generally have a Type 1 leg and a Type 2 leg. For this more common situation the total flight time to Jupiter would be about 3.4 years, which compares favorably with the 2.5 Hohmann flight time. With these trajectory modifications, the distances of closest approach may be well above all the planetary atmospheres.

The second example (see figure 2) illustrates a profile of the form Earth-Venus-Mars-Earth-Jupiter. Its trajectory characteristics are given in Table 2. One notices that in this case the total flight time is approximately 5.1 years or about twice as long as the Hohmann flight time. Using the same high energy chemical rocket engine, the mass ratio becomes .38. The distance of closest approach is about 200 km greater than that in the previous example (although it is still negative). The last example illustrates a Gravity Thrust trajectory which enables one space vehicle to fly-by almost all the planets in the Solar System (with the exception of Mercury and Pluto). The total flight time is 19.5 years, about 10 years less than the Hohmann flight time to Neptune. The trajectory characteristics are shown in Table 3. In this trajectory all the distances of closest approach are positive. The mass ratio corresponding to the oxygen-hydrogen engine is approximately .32. The mass ratio for the direct flight Earth-Neptune minimum energy trajectory would be .14. By increasing the injection velocity to about 8.1 km/sec and changing the profile to Earth-Jupiter-Saturn-Uranus-Neptune, it is possible to reach Neptune in about 8.5 years.[8] However, the mass ratio would be .15. It should be noted that since the quality of radio transmission over very great distances increases rapidly with increasing antenna size, missions to Neptune will require extremely large space-craft antennas. The vehicle's total mass must therefore be quite high and the mass ratio will have to be kept as high as possible. A sacrifice of ten years in order to raise the mass



$T_1$ = December 21, 1971
$T_2$ = December 10, 1972
$T_3$ = December 7, 1973
$T_4$ = June 20, 1974
$T_5$ = December 27, 1976

Fig. 2 Earth - Venus - Mars - Earth - Jupiter

## TABLE 1

ΔV= 4.06 km/sec

| PLANET | DATE | HEV | T | Θ | a | e | DOCA | TISI | DA | TDA | IMPV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EARTH | 3/18/75 | 4.14 | | | | | | | | | |
| | | | 349.6 | 457.1 | 0.795 | 0.252 | | | | | |
| VENUS | 3/1/76 | 9.06 | | | | | 669.0 | 1.55 | 43.3 | 5.8 | 6.69 |
| | | | 597.7 | 472.9 | 1.279 | 0.449 | | | | | |
| EARTH | 10/20/77 | 13.73 | | | | | -421.8 | 1.54 | 30.4 | 6.9 | 7.19 |
| | | | 999.9 | 139.7 | 3.158 | 0.716 | | | | | |
| JUPITER | 7/16/80 | 5.73 | | | | | | | | | |

## TABLE 2

ΔV= 4.10 km/sec

| PLANET | DATE | HEV | T | Θ | a | e | DOCA | TISI | DA | TDA | IMPV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EARTH | 12/21/71 | 4.25 | | | | | | | | | |
| | | | 354.0 | 457.8 | 0.818 | 0.214 | | | | | |
| VENUS | 12/10/72 | 6.96 | | | | | 264.8 | 1.96 | 61.7 | 8.0 | 7.14 |
| | | | 362.8 | 229.4 | 1.227 | 0.415 | | | | | |
| MARS | 12/ 7/73 | 11.11 | | | | | 356.6 | 1.17 | 9.7 | 4.4 | 1.88 |
| | | | 194.2 | 211.7 | 1.290 | 0.392 | | | | | |
| EARTH | 6/20/74 | 10.93 | | | | | -218.4 | 1.96 | 41.2 | 8.7 | 7.68 |
| | | | 921.7 | 151.7 | 2.995 | 0.677 | | | | | |
| JUPITER | 12/27/76 | 5.98 | | | | | | | | | |

## TABLE 3

ΔV = 4.87 Km/sec

| PLANET | DATE | HEV | T | Θ | a | e | DOCA | TISI | DA | TDA | IMPV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EARTH | 12/31/71 | 6.25 | | | | | | | | | |
| | | | 335.3 | 433.0 | 0.826 | 0.258 | | | | | |
| VENUS | 11/30/72 | 8.68 | | | | | 2241.5 | 1.60 | 39.9 | 5.6 | 5.92 |
| | | | 376.7 | 247.3 | 1.230 | 0.435 | | | | | |
| MARS | 12/12/73 | 11.59 | | | | | 312.1 | 1.13 | 9.1 | 4.0 | 1.83 |
| | | | 190.5 | 209.9 | 1.312 | 0.406 | | | | | |
| EARTH | 6/20/74 | 11.31 | | | | | 92.9 | 1.89 | 37.9 | 8.2 | 7.35 |
| | | | 870.5 | 146.7 | 2.988 | 0.679 | | | | | |
| JUPITER | 11/7/76 | 6.02 | | | | | 284632.1 | 147.67 | 130.4 | 19.2 | 10.92 |
| | | | 1567.5 | 130.2 | 23.370 | 0.800 | | | | | |
| SATURN | 2/21/81 | 7.61 | | | | | 121396.3 | 150.96 | 130.0 | 43.9 | 11.91 |
| | | | 2154.0 | 77.6 | 8.157 | 2.169 | | | | | |
| URANUS | 1/15/87 | 11.15 | | | | | 186180.0 | 107.14 | 20.9 | 14.1 | 4.04 |
| | | | 1643.4 | 22.4 | 5.598 | 3.485 | | | | | |
| NEPTUNE | 7/16/91 | 12.79 | | | | | | | | | |

ratio from .15 to .32 is an unreasonable penalty unless, of course, one is interested in using this time to monitor the deep space interplanetary environment.

A detailed analysis of the above examples is beyond the scope of this paper. However, I feel that these and similar profiles, such as Earth-Mars-Earth-Jupiter, Earth-Venus-Earth-Mars-Jupiter, etc., are extremely important because they will enable massive vehicles to reach Jupiter and hence the entire Solar System[12] with injection velocities just slightly higher than the minimum injection velocities required to reach Venus. Studies are now being undertaken to determine launch opportunities and flight times required for various Gravity Thrust trajectories to the Jovian mass field.

## Interplanetary Transportation Networks

In the introduction, it was pointed out that any interplanetary space ship designed to accommodate several hundred passengers in reasonable comfort for several months will have to be very massive. This is because each passenger will require at least 20 to 50 times his own mass in life support equipment. This estimate includes living essentials, special structural design and materials, etc.--in short, the sum total of the mass which could be eliminated by redesigning the ship for non-human cargo. The "brute force" technique of designing a space ship which could transfer great numbers of people from the surface of one planet to the surface of another would require so much energy that the concept borders on the realm of science fiction.

There are some obvious design techniques which could improve this situation. For example, the great mass of life support equipment required to keep the passengers comforable during their long space voyage is superfluous during the relatively brief launching and landing phases. Much energy could be saved if all this equipment were left in orbit rather than carried with the passengers down to a planet's surface. Consequently the earliest space pioneers such as Goddard and Oberth suggested that the space liners should operate between planetary parking orbits instead of planetary surfaces. A subsystem of much smaller ferry vehicles would then be designed for each planet in the network to transport passengers between orbiting "space ports" in the parking orbits and various surface facilities. This would greatly reduce the propulsion requirements of the interplanetary space liners, and therefore make the concept at least feasible. However, since this design plan will require major propulsive manuevers such as injections onto interplanetary trajectories and decelerations into parking orbits, the ship's propulsion system will still have to deal with the initial mass problem (which would be quite formidable since the ship's mass will be tremendous). Furthermore, all injections onto interplanetary transfer trajectories to a particular planet will have to be accomplished during a relatively short period when the required injection energies are at a minimum (unless, of course, one has engines of almost unlimited power, in which case our discussion becomes purely academic). The time intervals between these launch opportunities are equal to the launch planets' and arrival planets' synodic period. These time intervals can be quite long (780 days for transfers between Earth and Mars; 584 days for transfers between Earth and Venus). Hence the space ships in this network will have to spend long periods of time in various parking orbits, waiting for the desired launch opportunities--more time, in fact, than would be required for many voyages.

I will now introduce[5] an interplanetary transportation network which will almost completely nullify the initial mass problem affecting the design of the main space ships and which will, at the same time, significantly improve the parking orbit waiting time situation. Before going into any details, I will first give a brief conceptual description of this network. The transition from the surface-to-surface concept to the parking orbit-to-parking orbit concept of network design was motivated by the fact that it is not necessary to bring the entire space ship down to a planet's surface for the passengers to reach it. The idea behind the network I shall now describe arises from the fact that it is not even necessary to accelerate and decelerate the entire space ship in the process of transferring its passengers from an orbiting space port of one planet to an orbiting space port of another planet. If a second ferry vehicle subsystem can be designed for this purpose, the large space ships need not make any thrusting maneuver during a planetary encounter. A space ship can simply "coast" past a planet, using Gravity Thrust to direct it toward an encounter with another planet; the process can be repeated indefinitely. The ferry vehicles in the second subsystem (which I call "rendezvous modules") will be much smaller than the main space liners and will have a capacity of, perhaps, 50 passengers. Many of these modules can be used to transfer hundreds of passengers between various orbiting space ports and a single space liner during its encounter phase. The burden of accelerating this strictly passenger mass can thereby be distributed among the several rendezvous molecules. The entire network may involve several dozen massive space liners, all moving simultaneously on "never ending" journeys around the planets. This completes the basic conceptual description.

The actual construction of the interplanetary space liners will take place in vast orbiting "ship yards" equipped with all the facilities required to sustain hundreds of astronautical construction works for weeks at a time. Since the ships will be designed for maximum passenger comfort, some form of artificial gravity will be desired. Hence the ship's overall shape can be spherical or toroidal (resembling a huge innertube). During its flight around the planets, a slow constant spin will then induce the desired artificial gravity environment. The ship's overall size will range from 100 to 1,000 meters across. It will contain private living quarters, dining rooms, recreation areas, etc., --in short, everything one might find on modern ocean liners, but scaled up so as to be adequate for journeys of one or two years. The ships will contain onboard repair facilities which will enable major repairs to be undertaken while they are far away from any planet. They will also be supplied with vast quantities of rocket fuel for the rendezvous modules. In short these ships can be described as small, compact cities moving continuously from planet to planet.

When the construction of each ship is completed, preparations are made for its injection. All preparations prior to injection must be completed according to a strict time schedule to satisfy the demanding trajectory requirements. A space liner's interplanetary trajectory profile can be described by $P_1^j$-$P_2^j$-$P_3^j$-... where $P_1^j$ = Earth and $P_2^j$ = Venus or Mars. The symbol $P_i^j$ refers to the i'th planet encountered by the j'th space liner in the network. The Gravity Thrust received from each successive planetary encounter $P_i^j$ is the only thrust force used to propel the ship to the next planet $P_{i+1}^j$. Therefore, it is necessary to apply conventional rocket thrust (i.e., reaction thrust) only once, to inject the ship onto its initial transfer trajectory $P_1^j$-$P_2^j$. Thereafter the ship's guidance system takes over complete trajectory control. This initial transfer is chosen so that the required injection $\Delta V$ is an absolute minimum with respect to possible fixed trajectory constraints such as sufficiently great distances of closest approach at each successive planetary encounter. Preliminary calculations show that these required $\Delta V$'s will be approximately 3.7 km/sec or less. Hence it will be possible even for relatively weak second or third generation nuclear propulsion injection engines (with specific impulse in the neighborhood of 1,200 seconds) to launch relatively massive (first generation) space ships. Moreover, when the power of these injection engines is increased indefinitely, the space liner's mass can be increased also, but by proportions hundreds of times greater than would be possible without Gravity

Thrust. The injection will be extremely accurate, hence all subsequent trajectory corrections will be infinitesimal. The on-board rocket thrusts which will be required from time to time in order to maintain high trajectory accuracy can be assumed to be very small due to the high initial injection accuracy.

When the injection time approaches, passengers for the initial voyage board the ship with a full complement of supplies. Gigantic nuclear injection engines are brought into position and attached to the space ship. When the precisely calculated moment for injection occurs, the engines are started, sending the space liner on its perpetual journey around the planets. After the injection is accomplished, the engines are disconnected and sent back toward the Earth to rendezvous with another orbiting construction area for use in other injections.

As mentioned above, the complete network will consist of the main interplanetary space liners, a system of rendezvous modules operating between the space liners and various orbiting space ports, and a system of ferry vehicles operating between the space ports and surface facilities. It is natural to assume that the first planets to be colonized will be Mars and Venus. Thus if the first interplanetary transportation networks include only the Earth, Venus and Mars, the two secondary transportation subsystems can be designed to take maximum advantage of planetary atmospheres. The SCRAMJET[15] concept would be a most efficient design for the ferry vehicles providing transportation between various airports on the Earth's surface and various orbiting space ports. Furthermore, it does not seem unreasonable to assume that the SCRAMJET principle can be made to operate in other planetary atmospheres, such as those on Venus and Mars. Operation in the Martian atmosphere may, however, require difficult modifications, since that atmosphere is extremely tenuous.

The design of the rendezvous modules can also make use of planetary atmospheres. For example, after leaving a space liner with a load of passengers, a module could use atmospheric braking forces to provide almost all the energy required to slow it down before its rendezvous with an orbiting space port. This would greatly reduce the amount of fuel which would have to be supplied to the module by the space ship for this task. However, these modules will have to be equipped with the most powerful nuclear rocket engines in order to accelerate a load of passengers from an orbiting space port and rendezvous with a passing space liner. After completing the rendezvous, the modules can be placed on "automatic pilot" to keep them on an interplanetary trajectory very close to the space liner for use during future planetary encounters. Supplies for the main space liners can be taken aboard during each successive Earth encounter either by means of specially designed cargo modules or in large cargo compartments of the passenger rendezvous modules.

## The Search for Network Routes

The most important aspects of the interplanetary transportation network described above are the trajectories used by the great space liners. The network will be only as good as the routes of the "interplanetary highways" it follows. Discovering the best highways will be no easy task. I will not enter into a technical discussion of multiple encounter, Gravity Thrust trajectories in this paper - readers interested in such a discussion should consult reference 11. It is important, however, to point out the tremendous computational problems that must be dealt with when Gravity Thrust trajectories involving many successive planetary encounters are contemplated.

The initial conditions upon which a trajectory calculation is based are given by specifying the launch date $T_1$, the first planetary encounter date $T_2$, and the particular planets in the specified profile $P_1$-$P_2$-$P_3$-. . . -$P_n$, where n is any arbitrarily large integer. Successive encounters with the same planet (as for example - Mars - Venus - Venus - Earth -) are ruled out. Hence the total number of possible profiles involving n-1 encounters where $P_1$= Earth is $8^{n-1}$. Since each space liner will be very expensive, and must remain in actual use for long periods of time, its trajectory must be determined for many years following its initial launch date $T_1$. The trajectory profile must be calculated as a unit, rather than in segments, because it may turn out that a given trajectory cannot extend beyond $P_n$ without requiring unreasonably long flight times for the $P_n$-$P_{n+1}$ leg. In other words, before each space ship can be launched its trajectory $P_1^j$ - $P_2^j$ - . . . - $P_n^j$ must be calculated for relatively large n (depending upon the particular planets in the profile) with little option for subsequent change. For example, if the planets in the profile are restricted to the Earth, Venus and Mars, then n should be greater than 30 if the trajectory is to extend over a period of 30 years. Calculation of the network trajectories will be extremely difficult because the total number of encounters involved in any single profile trajectory may exceed 25 or 30, and the initial conditions do not uniquely determine the trajectory. To illustrate the great computational problems one must face, let us suppose one wishes to analyse all possible profiles involving the Earth, Venus and Mars with n-1 encounters, given only $P_1$, $T_1$, $P_2$ and $T_2$. If all the heliocentric transfer angles $\Theta$ swept out about the sun between successive encounters are to be less than 540°, each trajectory leg $P_i$ - $P_{i+1}$ can have, in general, a maximum of 6 different intercept dates $T_{i+1}$ at $P_{i+1}$ which will have the same departing energy at $P_i$ relative to $P_i$ $(i \geq 3)$. Consequently, for each particular profile there may be a total of $6^{n-2}$ different trajectories satisfying the initial conditions. Thus the total number N(n) of different trajectories theoretically possible is

$$N(n) = 12^{n-2} \qquad (2)$$

For the case n= 30 this number becomes $9 \times 10^{30}$. Moreover, for a complete analysis corresponding to the given $P_1$ - $P_2$ launch opportunity period a net[11] of trajectories with different $T_1$ and $T_2$ dates will have to be calculated. This net may involve 500 "points" $(T_1, T_2)$ in the $T_1$, $T_2$ plane. This fact may raise the total number of possible trajectories to $4.5 \times 10^{33}$. Since several of these $P_1$ - $P_2$ launch opportunities may have to be investigated, one is left with a number of different possible trajectories enormous beyond comprehension. The cost of computing all these trajectories would be greater than the total construction costs of the transportation network itself!

Although a "brute force" numerical attack on this problem is impossible, special computing techniques will automatically reject unfavorable trajectories before they are actually calculated. During the early stages of computation, these special techniques monitor a few critical factors upon which the characteristics of significant portions of possible trajectories depend. With the aid of these techniques, only an infinitesimal fraction of the total number of possible trajectories need be seriously investigated. This drastically reduced range of possibilities still presents a formidable computational task, however. In the above case where n= 30 the problem must be processed on a computer at least as powerful as the CDC 6600.

The trajectories shown in Tables 4 through 8 were calculated at the University of California Computer Facility at Berkeley on a CDC 6400. These trajectories are intended to show that the main space liners in the interplanetary transportation network described in this paper can in fact be propelled around the Solar System solely by Gravity Thrust. Of course, since these examples are not the results of any large scale effort to compute a suitable trajectory network, they should be viewed as poor choices for such a network.

Table 4 is an example of a trajectory designed to fly a space liner back and forth continuously between Earth and Venus. The average flight time

## TABLE 4

ΔV = 3.67 km/sec

| PLANET | DATE | HEV | T | Θ | a | e | DOCA | TISI | DA | TDA | IMPV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EARTH | 11/1/73 | 3.18 | | | | | | | | | |
| | | | 154.0 | 198.4 | 0.855 | 0.160 | | | | | |
| VENUS | 4/4/74 | 5.16 | | | | | 18844.4 | 2.63 | 38.4 | 3.9 | 3.39 |
| | | | 299.4 | 251.0 | 1.016 | 0.288 | | | | | |
| EARTH | 1/29/75 | 9.03 | | | | | 19637.1 | 2.29 | 18.2 | 2.5 | 2.86 |
| | | | 342.5 | 417.4 | 0.868 | 0.312 | | | | | |
| VENUS | 1/6/76 | 10.54 | | | | | 8855.0 | 1.33 | 18.8 | 2.7 | 3.45 |
| | | | 392.3 | 307.1 | 1.117 | 0.410 | | | | | |
| EARTH | 2/1/77 | 13.01 | | | | | 18270.0 | 1.61 | 10.0 | 3.3 | 2.27 |
| | | | 551.7 | 485.4 | 1.194 | 0.424 | | | | | |
| VENUS | 8/7/78 | 9.35 | | | | | 9095.9 | 1.50 | 22.6 | 3.4 | 3.67 |
| | | | 372.5 | 423.5 | 0.916 | 0.308 | | | | | |
| EARTH | 8/15/79 | 8.85 | | | | | 18685.0 | 2.40 | 19.4 | 5.7 | 2.99 |
| | | | 250.8 | 215.3 | 0.968 | 0.277 | | | | | |
| VENUS | 4/21/80 | 6.87 | | | | | 60121.7 | 2.01 | 10.8 | 1.6 | 1.29 |
| | | | 467.4 | 492.0 | 1.026 | 0.316 | | | | | |
| EARTH | 8/2/81 | 9.95 | | | | | 13491.6 | 2.15 | 19.4 | 4.5 | 3.35 |
| | | | 257.6 | 308.5 | 0.881 | 0.361 | | | | | |
| VENUS | 4/16/82 | 12.18 | | | | | 59971.4 | 1.16 | 3.7 | 0.6 | 0.78 |
| | | | 223.1 | 164.9 | 0.930 | 0.376 | | | | | |
| EARTH | 11/25/82 | 10.96 | | | | | 57888.0 | 1.91 | 5.6 | 2.1 | 1.08 |
| | | | 359.3 | 407.2 | 0.917 | 0.377 | | | | | |
| VENUS | 11/20/83 | 12.27 | | | | | 6501.6 | 1.14 | 16.8 | 3.2 | 3.59 |
| | | | 569.6 | 510.3 | 1.210 | 0.476 | | | | | |
| EARTH | 6/11/85 | 14.43 | | | | | 17770.5 | 1.49 | 8.4 | 2.5 | 2.12 |
| | | | 307.1 | 173.9 | 1.065 | 0.476 | | | | | |
| VENUS | 4/14/86 | 14.97 | | | | | 4306.3 | .94 | 14.0 | 2.4 | 3.66 |
| | | | 117.2 | 242.4 | 0.816 | 0.418 | | | | | |
| EARTH | 8/10/86 | 10.71 | | | | | | | | | |

## TABLE 5

ΔV = 3.65 Km/sec

| PLANET | DATE | HEV | T | θ | a | e | DOCA | TISI | DA | TDA | IMPV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EARTH | 5/14/75 | 3.09 | | | | | | | | | |
| | | | 162.0 | 191.5 | 0.869 | 0.170 | | | | | |
| VENUS | 10/23/75 | 5.16 | | | | | 16814.3 | 2.62 | 40.7 | 4.7 | 3.59 |
| | | | 276.5 | 238.7 | 0.994 | 0.277 | | | | | |
| EARTH | 7/26/76 | 7.99 | | | | | 32634.8 | 2.67 | 15.8 | 2.6 | 2.20 |
| | | | 362.1 | 424.7 | 0.892 | 0.302 | | | | | |
| VENUS | 7/23/77 | 9.39 | | | | | 1404.8 | 1.49 | 38.4 | 6.2 | 6.18 |
| | | | 495.1 | 261.6 | 1.383 | 0.493 | | | | | |
| MARS | 11/30/78 | 10.63 | | | | | 417.0 | 1.20 | 10.4 | 4.3 | 1.92 |
| | | | 606.9 | 396.9 | 1.314 | 0.500 | | | | | |
| EARTH | 7/29/80 | 14.82 | | | | | 8225.7 | 1.46 | 12.7 | 5.2 | 3.28 |
| | | | 535.5 | 525.4 | 1.144 | 0.473 | | | | | |
| VENUS | 1/16/82 | 15.11 | | | | | 2535.6 | 0.93 | 16.3 | 5.8 | 4.27 |
| | | | 400.7 | 399.5 | 1.006 | 0.452 | | | | | |
| EARTH | 2/20/83 | 13.74 | | | | | 4519.8 | 1.53 | 18.7 | 6.3 | 4.46 |
| | | | 441.9 | 230.4 | 1.260 | 0.466 | | | | | |
| VENUS | 5/7/84 | 10.81 | | | | | 247412.8 | 1.20 | 1.2 | 0.3 | 0.23 |
| | | | 470.8 | 306.5 | 1.249 | 0.463 | | | | | |
| EARTH | 8/21/85 | 13.66 | | | | | 7484.9 | 1.57 | 15.4 | 5.3 | 3.65 |
| | | | 318.1 | 316.6 | 1.047 | 0.456 | | | | | |
| MARS | 7/5/86 | 7.91 | | | | | 558.6 | 1.58 | 17.0 | 5.1 | 2.33 |
| | | | 109.6 | 96.3 | 1.125 | 0.424 | | | | | |
| VENUS | 10/23/86 | 10.85 | | | | | 10077.3 | 1.30 | 16.8 | 3.9 | 3.16 |
| | | | 301.2 | 305.4 | 0.964 | 0.358 | | | | | |
| EARTH | 8/20/87 | 10.34 | | | | | | | | | |

## TABLE 6

$\Delta V = 3.67$ km/sec

| PLANET | DATE | HEV | T | Θ | a | e | DOCA | TISI | DA | TDA | IMPV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EARTH | 11/1/73 | 3.18 | | | | | | | | | |
| | | | 154.0 | 198.4 | 0.855 | 0.160 | | | | | |
| VENUS | 4/4/74 | 5.16 | | | | | 18844.4 | 2.63 | 38.4 | 3.9 | 3.39 |
| | | | 299.4 | 251.0 | 1.016 | 0.288 | | | | | |
| EARTH | 1/29/75 | 9.03 | | | | | 19637.1 | 2.29 | 18.2 | 2.5 | 2.86 |
| | | | 342.5 | 417.4 | 0.868 | 0.312 | | | | | |
| VENUS | 1/6/76 | 10.54 | | | | | 8855.0 | 1.33 | 18.8 | 2.7 | 3.45 |
| | | | 392.3 | 307.0 | 1.117 | 0.410 | | | | | |
| EARTH | 2/1/77 | 13.01 | | | | | 75791.8 | 1.61 | 3.2 | 0.5 | 0.73 |
| | | | 510.0 | 418.7 | 1.180 | 0.418 | | | | | |
| VENUS | 6/26/78 | 9.29 | | | | | 5379.4 | 1.50 | 28.6 | 5.8 | 4.59 |
| | | | 443.2 | 518.0 | 0.957 | 0.289 | | | | | |
| EARTH | 9/13/79 | 9.80 | | | | | 3286.7 | 2.16 | 34.9 | 8.0 | 5.89 |
| | | | 633.8 | 422.1 | 1.306 | 0.354 | | | | | |
| MARS | 6/7/81 | 6.34 | | | | | 2605.7 | 2.03 | 17.4 | 2.3 | 1.91 |
| | | | 329.2 | 232.4 | 1.177 | 0.391 | | | | | |
| VENUS | 5/3/82 | 7.16 | | | | | 900.2 | 1.94 | 56.8 | 9.5 | 6.80 |
| | | | 537.5 | 464.4 | 1.183 | 0.391 | | | | | |
| EARTH | 10/22/83 | 12.14 | | | | | 38565.3 | 1.74 | 6.5 | 2.0 | 1.38 |
| | | | 340.9 | 223.4 | 1.105 | 0.383 | | | | | |
| VENUS | 9/27/84 | 9.33 | | | | | 5196.2 | 1.51 | 28.8 | 5.2 | 4.63 |
| | | | 802.8 | 490.6 | 1.536 | 0.534 | | | | | |
| MARS | 12/9/86 | 12.69 | | | | | 1936.1 | 0.98 | 5.4 | 1.5 | 1.21 |
| | | | 458.3 | 148.7 | 1.412 | 0.535 | | | | | |
| EARTH | 3/11/88 | 16.37 | | | | | 14789.9 | 1.29 | 7.5 | 2.3 | 2.15 |
| | | | 510.4 | 399.1 | 1.200 | 0.508 | | | | | |
| VENUS | 8/4/89 | 15.38 | | | | | 122.0 | 0.92 | 20.8 | 3.8 | 5.56 |
| | | | 216.6 | 317.4 | 0.789 | 0.412 | | | | | |
| EARTH | 3/8/90 | 10.79 | | | | | 1179.2 | 1.94 | 36.3 | 2.6 | 6.73 |
| | | | 197.7 | 220.3 | 1.197 | 0.357 | | | | | |
| MARS | 9/22/90 | 6.76 | | | | | 2891.6 | 1.84 | 14.9 | 2.9 | 1.75 |
| | | | 302.8 | 250.8 | 1.109 | 0.391 | | | | | |
| VENUS | 7/22/91 | 9.35 | | | | | | | | | |

## TABLE 7

ΔV= 3.67 km/sec

| PLANET | DATE | HEV | T | Θ | a | e | DOCA | TISI | DA | TDA | IMPV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EARTH | 11/1/73 | 3.18 | | | | | | | | | |
| | | | 154.0 | 198.4 | 0.855 | 0.160 | | | | | |
| VENUS | 4/4/74 | 5.16 | | | | | 18844.4 | 2.63 | 38.4 | 3.9 | 3.39 |
| | | | 299.4 | 251.0 | 1.016 | 0.288 | | | | | |
| EARTH | 1/29/75 | 9.03 | | | | | 19637.1 | 2.29 | 18.2 | 2.5 | 2.86 |
| | | | 342.5 | 417.4 | 0.868 | 0.312 | | | | | |
| VENUS | 1/6/76 | 10.54 | | | | | 8855.0 | 1.33 | 18.8 | 2.7 | 3.45 |
| | | | 392.3 | 307.0 | 1.117 | 0.410 | | | | | |
| EARTH | 2/1/77 | 13.01 | | | | | 75791.8 | 1.61 | 3.2 | 0.5 | 0.73 |
| | | | 510.0 | 418.7 | 1.180 | 0.418 | | | | | |
| VENUS | 6/26/78 | 9.29 | | | | | 5379.4 | 1.50 | 28.6 | 5.8 | 4.59 |
| | | | 443.2 | 518.0 | 0.957 | 0.289 | | | | | |
| EARTH | 9/13/79 | 9.80 | | | | | 3286.7 | 2.16 | 34.9 | 8.0 | 5.89 |
| | | | 633.8 | 422.1 | 1.306 | 0.354 | | | | | |
| MARS | 6/7/81 | 6.34 | | | | | 2334.6 | 2.03 | 18.1 | 2.5 | 1.99 |
| | | | 307.8 | 198.4 | 1.173 | 0.387 | | | | | |
| VENUS | 4/11/82 | 7.53 | | | | | 57665.0 | 1.85 | 9.5 | 1.7 | 1.24 |
| | | | 531.1 | 470.9 | 1.165 | 0.387 | | | | | |
| EARTH | 9/24/83 | 12.06 | | | | | 37365.9 | 1.76 | 6.8 | 2.5 | 1.42 |
| | | | 396.0 | 293.9 | 1.139 | 0.382 | | | | | |
| VENUS | 10/24/84 | 8.11 | | | | | 7770.7 | 1.73 | 30.4 | 5.9 | 4.26 |
| | | | 275.0 | 184.6 | 1.197 | 0.394 | | | | | |
| MARS | 7/26/85 | 6.25 | | | | | 5542.4 | 2.28 | 12.6 | 4.2 | 1.37 |
| | | | 617.6 | 435.4 | 1.205 | 0.394 | | | | | |
| EARTH | 4/5/87 | 12.17 | | | | | 18243.7 | 1.74 | 11.3 | 2.6 | 2.40 |
| | | | 425.6 | 412.6 | 1.035 | 0.382 | | | | | |
| VENUS | 6/4/88 | 11.07 | | | | | 11957.4 | 1.28 | 14.7 | 3.0 | 2.83 |
| | | | 371.1 | 250.2 | 1.255 | 0.467 | | | | | |
| MARS | 6/10/89 | 8.71 | | | | | 3800.5 | 1.66 | 8.4 | 2.0 | 1.27 |
| | | | 672.0 | 424.9 | 1.334 | 0.428 | | | | | |
| EARTH | 4/13/91 | 12.55 | | | | | 53391.0 | 1.69 | 4.7 | 0.9 | 1.02 |
| | | | 551.9 | 440.1 | 1.228 | 0.409 | | | | | |
| VENUS | 10/16/92 | | | | | | | | | | |

## TABLE 8

ΔV= 4.92 km/sec

| PLANET | DATE | HEV | T | Θ | a | e | DOCA | TISI | DA | TDA | IMPV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EARTH | 12/30/71 | 6.34 | | | | | | | | | |
| | | | 335.0 | 432.2 | 0.826 | 0.260 | | | | | |
| VENUS | 11/29/72 | 8.74 | | | | | 2318.2 | 1.59 | 39.2 | 5.6 | 5.87 |
| | | | 376.2 | 247.9 | 1.229 | 0.435 | | | | | |
| MARS | 12/10/73 | 11.60 | | | | | 262.0 | 1.13 | 9.2 | 3.9 | 1.85 |
| | | | 189.9 | 208.9 | 1.315 | 0.405 | | | | | |
| EARTH | 6/18/74 | 11.22 | | | | | 95.5 | 1.91 | 38.3 | 8.2 | 7.37 |
| | | | 840.0 | 145.6 | 2.994 | 0.679 | | | | | |
| JUPITER | 10/5/76 | 6.06 | | | | | 236356.6 | 146.50 | 133.3 | 23.3 | 11.13 |
| | | | 1590.1 | 132.8 | 22.034 | 0.789 | | | | | |
| SATURN | 2/11/81 | 7.54 | | | | | 762688.5 | 153.23 | 53.2 | 12.6 | 6.75 |
| | | | 3609.8 | 273.9 | 5.72 | 0.901 | | | | | |
| EARTH | 12/31/90 | 25.80 | | | | | 8526.2 | 0.81 | 4.4 | 2.0 | 1.99 |
| | | | 624.2 | 75.8 | 3.29 | 0.843 | | | | | |
| JUPITER | 9/15/92 | 8.78 | | | | | 969653.9 | 121.14 | 75.5 | 88.1 | 10.75 |
| | | | 631.7 | 82.9 | 3.36 | 0.819 | | | | | |
| EARTH | 6/9/94 | 23.29 | | | | | | | | | |

between encounters is 333 days, or 251 days less than the synodic period of these planets. Other trajectories of this type also have this property. Therefore, a combination of several such trajectories will significantly reduce the waiting period between flight opportunities, which is often very long in parking-orbit-to-parking-orbit network designs. Notice that since the required $\Delta V$ is extremely small ($c_3 = 10$), an uprated Saturn V launch vehicle (such as the MLV-SAT-V-3B with the aero-spike second stage[16]) will be able to inject a 62,000 kgm vehicle onto this trajectory. It should be easy to construct a modest 5-man "first generation" interplanetary space ship of approximately this payload mass, since no major propulsive maneuvers will ever be required. The first few encounters can be used for manned Venus fly-by missions. Later on, when several ships of this type are sent on early network trajectories, they could play an important role in the design of early manned planetary landing expeditions.[11]

Table 5 is an example of a profile which will take a space ship around three planets -- Earth, Venus and Mars. In this case the average flight time between encounters is 374 days. With the aid of a nuclear rocket injection engine (Isp= 850 seconds) capable of injecting a 586,000 Kgm payload from an initial orbital mass of 900,000 Kgm, a half-million Kgm space vehicle can be injected onto the first leg of this network trajectory. If an "Orion" nuclear pulse injection engine (Isp= 2500 seconds) is used, the payload can be increased to 775,000 kgm. With this mass available, the vehicle can begin to take the shape of a true space liner.

A trajectory profile involving 16 planetary encounters is shown in Table 6. The first four legs of this trajectory are almost identical to the trajectory in Table 4. Notice that the flight time for the eleventh leg is 803 days. In a complete network employing several dozen space liners, there will probably be one liner on a trajectory passing Venus within a few weeks of Sept. 27, 1984, and encountering Mars with a transfer time of only 250 to 300 days. Passengers wishing to go to Mars from Venus will take this ship rather than the ship on the Table 6 trajectory. An example of a possible trajectory of such an alternative space liner is shown in Table 7. The last example, illustrated in Table 8, is intended to show that a single interplanetary transportation network can connect the inner planets with the outer planets -- it is not necessary to construct two fundamentally different networks to serve the two planetary groups. The individual space liners will be able to operate among both the inner and the outer planets. However, encounters involving Saturn, Uranus, Neptune or Pluto will generally require very long flight times (i.e., more than 5 years between encounters).

## CONCLUSION

If one looks into the future to contemplate how our rapidly advancing technology can be best applied to further our space program, it will become apparent that great scientific and technological breakthroughs must occur before men can truly master the far reaches of the Solar System. Instead of trying to master the Solar System, we should recognize how difficult this will be and try to live with it as it is, developing our strategy of exploration accordingly. The basic ideas in this paper are an expression of this philosophy.

As our space vehicles become more massive, and more sophisticated missions are contemplated, greater thrust forces will be required to change the vehicles' interplanetary trajectories. A mission designer should try to see nature as a potentially useful force which can help him attain his goals, rather than as an enemy which must be conquered through "brute force" rocket power. Nature has supplied us with a free and potentially powerful thrust source, Gravity Thrust, which may open the door to space missions previously considered impossible without the aid of the most advanced and most expensive propulsion systems. I am advancing the idea that there are two fundamentally different systems of vehicle propulsion -- the reaction rocket engine, and the "gravity engine." Other potential resources which nature has placed at our disposal are planetary atmospheres. A planetary atmosphere can be utilized in two ways. It can provide substantial braking forces to decelerate space vehicles, and it can accelerate them by providing mass to be expelled in a reaction jet like that described in the SCRAMJET concept.[15]

A systematic approach to mission design along these lines requires the development of several vehicle subsystems. An extremely accurate onboard planetary approach guidance system will of course be absolutely essential. However, before this can be achieved it will be necessary to determine planetary orbits with far more accuracy than is presently obtainable. Although it is tempting (and is to some extent possible) to construct a planetary approach guidance system by extending present earth-based guidance techniques,[17] temporary solutions can often mask the real problems and throw the overall situation out of focus. A suitable on-board guidance system must be able to operate over long periods of time in greatly varying interplanetary environments. The system must be able to sense accurately certain characteristic properties of many (if not all) celestial objects, depending upon the nature of the system (i.e., radio, optical, orbital, etc.). Hence some of our early planetary space probes should be programmed to obtain this vital information. The relatively low thrusts required by the system may be very efficiently provided by an ion engine. Such an ion thrust guidance system will be able to operate over long periods of time and hence can maintain very accurate trajectory control. Moreover, it may contribute to the overall trajectory design.

The development of heat shields for atmospheric braking should be pursued with more vigor. In a very real sense they can be viewed as extremely powerful retro rockets. Advances, however, will require fundamental breakthroughs in metallurgy and materials.

The SCRAMJET concept has great potential. It should provide a very economical means of ferrying large numbers of passengers and heavy cargos into planetary parking orbits from the surface of those planets which have atmospheres. Its development and use will play an important role in the strategy of space exploration I have described.

My concept of the interplanetary transportation network explained in this paper is based upon integration of the Gravity Thrust, atmospheric braking and SCRAMJET concepts into one total concept which I feel will offer the most economical interplanetary transportation system to large numbers of people -- especially if the network is confined to the planets Earth, Venus and Mars. The network can be started even before any manned interplanetary landing mission is carried out, and hence can play an important role in these first planetary landing missions.

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Sciences Meeting, Paper No. 65-90, Jan. 1965.

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AMERICAN ASTRONAUTICAL SOCIETY

# Regional Symposium
# On
# PLANETARY GEOLOGY AND GEOPHYSICS

Sponsored by
THE NEW ENGLAND SECTION
of the
AMERICAN ASTRONAUTICAL SOCIETY
and the
NEW ENGLAND ACADEMIC COMMUNITY

25-27 May 1967

The Sheraton Boston Hotel
The Prudential Center
Boston, Mass.

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## First Session:
## (9:00 to 11:00 AM 25 May 1967)

## THE ROLE OF PLANETARY GEOLOGY AND GEOPHYSICS IN THE SPACE EFFORT

Chairman: Dr. Fred Whipple, Smithsonian Astrophysical Observatory

"Greetings from the American Astronautical Society"
John L. Crone - Chairman, New England Section, AAS

"Exploration of the Solar System by Manned and Unmanned Systems"
Gordon R. Woodcock - Marshall Space Flight Center

"Real Time Synoptic Systems in Geospheres"
Dr. Raymond L. Bisplinghoff - MIT

"Geophysical Geological Astronomical Biological and other Applications of Apollo Space Systems"
Leonard M. Tinnan - NAA

"Use of Space Systems for Planetary Geology and Geophysics"
Dr. Fred Whipple - Smithsonian Astrophysical Observatory

"Unmanned Exploration of the Inner Planets, the Outer Planets, and Near Interstellar Space"
Dr. Maxwell W. Hunter II - Lockheed Missiles and Space Co

"Gravity Assisted Multiple Mission Trajectories"
John Nichoff

"Orbital Surveys of the Earth"
Dr. William A. Fischer - U.S. Geological Survey

"Constraints on the Grand Design"
David Knapton - Browne and Shaw Research Co.

"Biochemical Aspects of Hibernation"
Dr. Leonard R. Avelrod - S.W. Foundation for R&D

"Planetary Exploration from Orbiting Space Stations"
Dr. W. E. Stoney - NASA Manned Spacecraft Center

"Space Mission Planning"
Dr. C. A. Stone - IIT Research Institute

"The Origin of the Solar System"
Dr. A. G. W. Cameron - Yeshiva University

"Science Goals Effectiveness for Scientific Space Missions"
Dr. D. A. Cohen - Philco - Ford

"Interstellar Matter"
Dr. Fred M. Johnson - EOS

Panel Discussion: (11:00 to 11:30 AM)

Co-Chairmen: Dr. A. G. W. Cameron - Yeshiva University
Rev. Dr. James Skehan - Boston College
Dr. Robert Forward - Highes Research Labs.

Panel Editors: Saul Kent - Cryonics Inc.
Dr. Richard T. Wareham - D.C. Heath Publ. Co.

Luncheon: (12:00 to 1:30 PM)
Speaker: "Bio-Cryonics and the Grand Design"
Prof. R. C. W. Ettinger

## Second Session:
## (2:00 to 4:30 PM 25 May 1967)

## GEOPHYSICAL ENVIRONMENTS

Chairman: Rev. Dr. S. J. Linehan - Boston College Observatory

"Geological Time and Space Research"
Dr. Eugene Shoemaker - U.S. Geological Survey

"Atmosphere of the Sun and Other Stars"
Dr. Hong-Yee Chiu - Goddard Institute for Space Studies

"Interstellar Space in the Neighborhood of the Sun"
Dr. John Harrington - MIT Space Science Center

"Planetary Systems of Stars in the Neighborhood of the Sun"
Dr. Peter van de Kamp - Sproul Observatory

"Small Bodies of the Solar System"
Dr. John Wood - Smithsonian Observatory

"Planetary Interiors"
Dr. Thomas Turcott - Boston College Observatory

"The Upper Atmosphere of the Earth"
Dr. C. G. Walker - Goddard Space Flight Center

"Planetary Gravispheres"
Dr. Hubertus Strughold - Aerospace Medical Research USAF

"Planetary Atmospheres and Telescopes"
Dr. Leo H. Narodny - Kollsman Inst. Co.

"Lithospheres: The Nature of the Solid State"
Dr. Robert M. Haag - Avco

"The Milky Way Galaxy and Galactic Zones"
Ben Bova - Avco

"A Preliminary Synthesis of the Geology of Mars"
George P. Zebal - Aeronotronics

"Interpretation Photometric - Polorimetric Observation of Planetary Surfaces"
W. G. Egan, K. M. Forman, E. A. Nowatzki - Grumman Aircraft

Panel Discussion: (4:30 to 5:00 PM)

Co-Chairmen: Dr. R. L. Bisplinghoff - MIT
Rabbi Leo Shubow - Temple ENAI BRITH

Question: "Is the Geosphere and Geomorphic Order Approach to Planetology Sufficient?"

Panel: Dr. C. W. Wolfe - Boston University
Rev. Dr. James Shahan - Boston College
Frederick I. Ordway III - General Astronautics
Dr. Loomis - Jet Propulsion
Dr. Robert D. Enzmann - Raytheon
Dr. Mohammed Gheith - Boston University

Panel Editor: Ben Bova - Avco

## Third Session:
## (9:00 AM to 1:00 PM 26 May 1967)

## INSTRUMENTATION REQUIREMENTS

Co-Chairmen: H. Philip Hovnanian - NASA Headquarters
Rev. Dr. John F. Devane - Weston Geophysical Observatory

"The New England Seismic Net, and the Gross Structural Geology of New England"
Dr. John F. Devane - Weston Geophysical Observatory

"Measurements Which can be Made from Weather Satellites"
Dr. I. Larry Goldberg - Goddard Space Flight Center

"Seismic Signatures"
G. H. Westby - Seismograph Service Co.

"Rough Landing Planetary Payloads"
Dr. Daniel N. Tompkins - Philco-Ford Co.

"Space and Bio-Cryonics"
Curtis Henderson - N. Y. Cryonics Co.

"Conceptual Design of an Active Seismic Experiment for the Lunar Surface"
Alen Baker - RCA

"Petrographic Image Enhancement"
Lawrence MacKenzie - Photo-Graphics, Inc.

"Solar Radio Astronomy"
Dr. Harriet H. Malitson - Goddard Space Flight Center

"Stellar Signatures and Use of Star Trackers in the Solar System and Interstellar Space"
Dr. John Goodlet - General Precision

"Detection of Biospheres"
Dr. Edward Botan - Avco

"Nuclear Particle Sensors"
James F. Lawrence - Raytheon

"Winds in the Terrestrial Mesosphere"
Dr. William Nordberg - Lab for Atmo. and Biological Sciences

Panel Discussion: (11:00 to 11:30 AM)

Chairman: Prof. Harrington - MIT

Question: "Is There an Effective Way to Describe Information Gathering Traverse by Sensors in General Across an Unknown Surface?"

Panel: James C. Hamilton - Atty.
Nicolaos Meliones - RCA

Panel Editor: Harold Buchbinder - Blawell Publishing Co.

## Fourth Session:
## (2:00 to 4:30 PM 26 May 1967)

## VEHICULAR AND COMMUNICATIONS REQUIREMENTS

Co-Chairmen: Dr. C. W. Wolfe - Boston University
Dr. Krafft A. Ahricke - Autonetics

"$I_{sp}$ as a Function of Propulsion Method"
Dr. Jack Martinez - TRW

"Unmanned Precursors and Manned Interstellar Vehicles"
Dr. George Moganthaler - The Martin Co.

"Interstellar Fusion Propulsion of Unmanned and Manned Vehicles"
Dr. Dwain Spencer - Jet Propulsion Lab

"Interplanetary Missions and Rendezvous Techniques"
Dr. Avedis A. Aintablian - Lockheed Missiles and Space Co.

"Planning a Lunar Exploration Program"
David Paul III - NASA

"Planetary Exploration with Voyager Class Vehicles"
John A. Gautraud - Avco

"Clear Air Turbulence and Atmospheric Circulation"
James Fisca - NBC

"Vehicular Requirements for Planetary and Transplanetary Exploration"
Dr. Krafft A. Ehricke - Autonetics

"Electro-Propulsion with Colloids"
Dr. Milton Farber - Maremont Co.

"Nuclear Ram-Jets"
Dr. A. Corbin - LTV

"Lunar Surface Nuclear Experiment Package"
Dr. D. B. Ebeoglu - Bendix Aerospace Systems

"Unmanned and Manned Systems to Comets"
Dr. Robert A. Park - TRW

"Minor Planet Research and Collision Avoidance"
Dr. Gerald A. Ouellete and Dr. John Neyhand - IBM

Panel Discussion: (4:30 to 5:00 PM)

Co-Chairmen: Dr. Jerry Grey - Princeton
William Pease - Raytheon

Question: "What is the Space Transportation Potential in the 1975-1990 Time Period?"

Panel: Dr. Franklin Diederich - Avco
Dr. W. N. Hess - NASA
Zarch Martin - NSSAVE
Pabrad A. Giragosian - Mug Flight Technologies
Earl Myers - Raytheon

Panel Editor: Fred Pohl - Galaxy Publ.

Cocktails: (6:00 to 6:30 PM)

Banquet: (6:30 to 7:30 PM)
Speaker: "Propulsion and Grand Design"
Dr. Jerry Gray - Princeton

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## Fifth Session:
## (9:00 to 11:00 AM 27 May 1967)

### DATA AND SAMPLE COLLECTION, PROCESSING AND DISSEMINATION

Co-Chairmen: Dr. Ronald Scott - Northeastern University
Dr. Nick De Claris - Cornell University

"Resolution and Instrument Contour Diagramming"
Dr. H. Philip Hovnanian - NASA

"Signals in Noise"
Dr. Harold R. Raemer - Northeastern University

"Manned Exploration of Space"
Frederick I. Ordway - Gen. Astronautics Res. Co.

"The Nature of Resolution"
Stephen P. Pustelnik - Raytheon

"Minimum Detectors and Samples in Dirt"
Dr. R. D. Enzmann - Raytheon

"Reduction of Data to Bits"
Dr. Oscar Lowen Schuss - Raytheon

"Traverses and Sampling Patterns as Matched Filters"
Dr. C. W. Wolfe - Boston University

"Convolution Techniques"
Anthony Di Nardo - Raytheon

"Technological and Operational Considerations Affecting Development of Re-Usable Launch Vehicles"
S. Enzer - NAA

"Observers and Observed, Receptors and Effectors"
Prof. Israel Katz - Northeastern University

"A Photometric Technique for Deriving Slopes from Lunar Orbitor Photography"
Jay Lambiotte and Glen Taylor - NASA, Langley

"The Importance of Quality Assurance and Reliability for Spacecraft Sterilization"
Herbert Schwartz - Avco

"Feedback and Automatic Control Systems"
Joseph F. Santacroce - Raytheon

"Bandwidth and Filtering"
Robert Stein - Raytheon

"Analysis of Short-Time Non-Recurring Phenomena"
Sidney Himmelstein - S. Himmelstein and Co.

"Ambiguity Functions"
Dr. Nick De Claris - Cornell University

"Space Environments"
Dr. H. T. McAdams - Cornell Aeronautical Lab.

"Synthetic Aperture Radar"
Paul Hill - Raytheon

Panel Discussion: (11:00 to11:30 AM)

Co-Chairmen: Prof. Israel Katz - Northeastern University
Dr. H. T. McAdams - Cornell Aeronautical Labs.

Question: "Can Radar Information and Sensor Theory be Generalized to Include All Forms of Information Acquisition?"

Panel: Lawrence MacKenzie - Photographics Inc.
Glenn H. Taylor and Jay Lambiotte - NASA
Sydney Himmelstein - Himmelstein & Co.
Victor K. McElheny - Boston Globe

Panel Editor: Wm. E. Bushnor - "Laser Focus"
Harry Stubbs - Milton Academy

Luncheon: (12:00 to 1:30 PM) Speaker: "Probing into Interstellar Space - The Steps in the Grand Design"
Dr. Robert Fernard - Hughes Aircraft

## Sixth Session:
## (2:00 to 4:30 PM 27 May 1967)

### SYSTEMS INTEGRATION AND SPACE MISSION PLANNING

Chairman: Dr. John Harrington - MIT Center for Space Research

"Trajectory Planning and Mission Analysis"
John Miller and Sam Wilson - TRW

"Theory of Systems Reliability"
Avery Hevesh and Zarch Martin - Avco

"Lunar Mission Planning from the Standpoint of Trajectories"
Dr. Paul Penzo

"Automatic Checkout"
John J. Baranofsky - Raytheon

"Space Mission Optimization with Lunar Programming"
Kurt Eisemann - Computer Usage Co.

"Trajectory Planning for Lunar Expeditions"
Dr. Hooker - NASA

"Optimization of Rocket Logistics"
Paul Hill - NASA, Langley

"Automatic Checkout of Systems"
Dr. Robert Turkington - RCA

"Psychological Considerations in the Selection of Astronauts"
Dr. Joseph F. Kubis - Fordham University

"Automatic Checkout of Space Systems"
Dr. Larry T. Mast - RAND

"Education for the Space Age"
William G. Rohrer

"Position of Moving Platforms in Aerospace"
Richard B. Headley - Raytheon

"Theory of System Integration"
Robert Shannon - Raytheon

"Interplanetary Transportation Networks"
Dr. Michael A. Minovitch, JPL

"Nuclear Missions for the Inner and Outer Solar System"
Dr. John F. McLaughlin - Lockheed Missiles and Space Co.

"Communication Enhancement During Planetary Entry"
J. Rossi - Raytheon

Panel Discussion: (4:30 to 5:00 PM)

Co-Chairmen: Dr. Joseph F. Kubis - Fordham University
Dr. McLaughlin - Lockheed

Question: "What is a System, a Sub-System? Is a System an Entity that can Reproduce Itself?"

Panel: George Rawcliffe - Bentley College
Rev. Dr. John Gunther
James Hammond - State College, Mass.
Dr. Brady Williamson - MIT
Dr. Frederick J. McGarry - MIT
Dr. Fred Moavenzadeh - MIT
Henry Olds - Harvard
Rev. Dr. Wm. R. Callahan

Panel Editor: Henry Stubbs - Milton Academy, Mass.

AN AMERICAN ASTRONAUTICAL SOCIETY PUBLICATION

# Volume 17
# Use of Space Systems for Planetary Geology and Geophysics

Edited by
**ROBERT DUNCAN ENZMANN**
Proceedings of an
AAS Symposium
held in Boston, Mass.
May 25 - 27, 1967

## AAS SCIENCE AND TECHNOLOGY SERIES
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