JET PROPULSION LABORATORY

INTEROFFICE MEMORANDUM
393.1-436
May 17, 1972

TO: R. D. Bourke

FROM: M. A. Minovitch MAM

SUBJECT: Unexplained 11 Month Delay in Getting JPL Clearance for the Paper Entitled "The Development of Gravity Thrust Space Trajectories"

In regards to our conversation Friday, 12 May, you gave me no official explanation why the paper I submitted 11 months ago entitled "The Development of Gravity Thrust Space Trajectories" has not yet been cleared for publication. Your personal explanation which you indicated is based upon the assumption that the public is simply not interested in facts behind significant breakthroughs in space travel. This should not be the reason for the delay. This judgement should be reserved for the editor of the publishing company.

I shall list below a sample of some major articles and publications that have presented completely erroneous accounts of this development.

1. Bane, D., (Herald Examiner Staff Writer), "First Stop: Jupiter", Los Angeles Herald Examiner, Wednesday, September 10, 1969. P. A12 (minor variations of this write-up appeared in syndicated articles of many newspapers all over the United States).

2. Flandro, G. A., "The Mechanics and Applications of the Planetary Swing-By Maneuvers in Interplanetary Mission Design", Proceedings of the Symposium on Space Projections from the Rocky Mountain Region, AAS, Denver, Colorado, July 15-16, 1968.

3. Ehricke, K., "Solar Transportation", Space Age in Fiscal Year 2001, Science and Technology Series, Vol. 10, (Proceedings of the Fourth AAS Goddard Memorial Symposium 15-16 March 1966) see in particular pages 171-180 (The Co-Chairman of the session in which this paper was presented was Maxwell Hunter II - who was also one of the editors of this volume)

4. Ross, S., "Trajectory Design for Planetary Mission Analysis", Recent Developments in Space Flight Mechanics. Science and Technology Series, Vol. 9 (Proceedings of the AAS/AIAA Special Astronautics Symposium, 29 December 1965, Berkeley, California), p. 4-17 (this account is actually very humerous when compared to what Hollister writes several years later in J. of Spacecraft and Rockets, Vol. 7, No. 10, October 1970, p. 1193).

This list could be continued on several more pages but it will suffice for my purposes. My point is that many professional astrodynamicists apparently will rather sacrifice the integrity of their chosen profession rather than accept a truth that might tarnish their image. By refusing to grant clearance of the paper in question, JPL may extend this immorality to an entire research center (i.e. JPL). If anyone on the Laboratory wishes to discuss the accuracy of the paper let him present his case to me personally.

On the other hand, this long IOM may be entirely uncalled for. The paper I submitted last year may have become lost. If this is the case, I would simply like to call attention to this fact. I am attaching another copy of the paper (which is a slightly improved version) for your convenience. The above references should be reviewed, however, to understand how serious this problem of misinformation really is.

I am hoping that the attached paper can be reviewed and cleared for publication in Astronautics and Aeronautics within a reasonable amount of time.

MAM:mmv

Attach.

cc: C. R. Gates
T. W. Hamilton
R. R. Stephenson

THE DEVELOPMENT OF GRAVITY THRUST SPACE TRAJECTORIES

by

Michael A. Minovitch

The concept of utilizing planetary gravitational perturbations as a substitute for on-board rocket engines to achieve propulsion-free interplanetary space travel throughout the Solar System has probably had more impact on trajectory design and mission planning than any development since nuclear rocket propulsion. This article is written to those scientists and engineers who have a professional interest in the field of astronautics and to those historians of science and technology who find it difficult to trace the origin and development of this concept.

Introduction

The concept of gravity thrust interplanetary space travel was born during the summer of 1961. It represented a complete break with traditional ideas about space travel and trajectory design. An extensive computational research

project involving the numerical analysis of gravity thrust space trajectories took place during the following three years (1961-64) at UCLA and JPL. Hundreds of hours of computer time were used on the largest computers. What made this long time and sometimes frustrating efforts worthwhile were the results. The concept, which may have appeared in 1961 as a rather sterile academic curiosity became a method for carrying out interplanetary missions previously thought impossible without super-sized launch vehicles. The history involving these early years is what follows.

Background

Any discussion involving the history of astrodynamics would be incomplete without mentioning the work of Walter Hohmann. In a sense, Hohmann can be called the Euclid of astrodynamics. He applied the general principles of two-body motion to the special case of space vehicles moving under the influence of the Sun. Hohmann incorporated his results with the famous rocket equation developed earlier by Tsolkovsky to produce the first comprehensive study of interplanetary flight mechanics for rocket propelled space vehicles.[1]

When a space vehicle approaches a planet on a free-fall reconnaissance trajectory, its motion is

determined by the gravitational attractions of the Sun and the planet. The trajectory determination becomes the famous unsolved three-body problem of celestial mechanics. Hohmann circumvented this problem by cancelling out the planetary perturbations through application of rocket thrust equal to the perturbing force, but of opposite direction (ref. 1, pp. 79-81). Thus, he viewed perturbations as annoying disturbances which tended to destroy constant elliptical motion about the Sun.

Although Hohmann had a tremendous impact on the new field of astrodynamics, not all subsequent researchers shared his view regarding perturbations. Lawden,[2] for example, pointed out that a space vehicle sent to Mars or Venus can save energy by taking advantage of possible lunar perturbations. Although his derivations concerning the numerical values of these savings were in excess of the actual values, he did manage to represent perturbations as a potential friend rather than a hindrance to astrodynamicists. It appears, however, that Lawden failed to recognize the fundamental role perturbations can play in trajectory design, or how they could be utilized most effectively.[3,4]

In his study of interplanetary reconnaissance trajectories, Hohmann suggested the possibility of sending one space vehicle on a non-stop, free-fall trajectory,

which would intercept the orbits of both Venus and Mars just as these planets were passing by, and return to Earth.[1] According to his design philosophy, the trajectory was a constant elliptical path made possible by cancelling out the perturbations of the intermediate planets with on-board rocket thrust.

By making use of Lawden's analysis, Crocco[5] managed to solve the perturbation problem in Hohmann's dual planet fly-by trajectory by a more sophisticated technique. He simply reversed the order of the Venus and Mars encounters and used the Venus perturbation to cancel out the effect of the Mars perturbation, thereby obtaining a final trajectory very close to his pre-calculated, unperturbed, constant, elliptical path. Unfortunately, underlying both Hohmann's and Crocco's trajectories is the fact that any constant elliptical path about the Sun, with aphelion outside the orbit of Mars and perihelion inside the orbit of Venus, requires considerable launch energy.

The fact that Crocco expended considerable analysis to obtain a trajectory close to a constant, perturbation-free, elliptical path demonstrates that he also viewed perturbations as basically undesirable in overall trajectory design. Consequently, these

trajectories cannot be considered as early examples of gravity thrust trajectories. Quite the contrary, they tended to resist the basic phenomena which is the crux of gravity thrust trajectory design, namely gravitational perturbations. This general point of view prevailed up to the early 1960's where trajectory analysts often solved the perturbation problem by either applying rocket thrust[6] as in Hohmann's solution, or by simply not allowing a free-fall vehicle to come very close to a passing planet.[7]

If one desired to design a trajectory which would take a vehicle from planet A to planet B, the logical procedure was to find a minimum energy constant eliptical path or Hohmann trajectory connecting these planets. When these classical procedures were used to obtain numerical orbit determinations via modern, high-speed, electronic digital computers, the results only confirmed the conclusion reached earlier by the crude, hand calculations of Hohmann and Oberth.[8] Except for relatively simply, fly-by missions to Mars or Venus, most interplanetary missions would require extremely high launch energies and/or very long flight times. The dual planet fly-by trajectories of Hohmann and Crocco were found to require so much energy that some analysts tended to view them (quite understandably) as "interesting academic pastimes" (ref. 7, ch. 5). Nevertheless, the early 1960's was an era of great enthusiasm for

space travel and rough designs for the required super boosters (known variously as Novas, Super-Novas, and Sea Dragons) were drawn.[9] References 10 and 11 will provide a fairly accurate picture of astrodynamics up to this period.

The Development of Gravity Thrust Space Trajectories

My association with the California Institute of Technology's Jet Propulsion Laboratory began in June of 1961 when I joined their Systems Analysis Section as a summer employee. At that time I had completed three years of graduate work at UCLA preparing for a doctorate in mathematics. My immediate goal was to study one-way interplanetary conic trajectories and to develop a solution which could replace the one then in use at JPL. A paper by Batten[12] was suggested as a possible aid in this study by Victor Clarke, Jr. who was then the head of JPL's trajectory group. This paper presented a detailed solution to the one-way problem by employing a relatively obscure set of equations known in Celestial Mechanics as Lambert's Theorem. By using this solution as a starting point, I constructed a slightly improved version and formulated it for possible use on a digital computer.[13] Batten's paper also introduced me to the problem of free-fall, round trip, interplanetary reconnaissance trajectories. Although his treatment of perturbations was basically correct, he appeared to take a rather neutral attitude regarding their potential usefullness in over-all trajectory design. However, he did emphasize the fact that free-fall

reconnaissance trajectory problems were basically three-dimensional in character. I became absorbed in a detailed mathematical study of the representation of general conic trajectories in three-dimensional space. The standard methods employing classical orbital elements are quite adequate for observational astronomers but not for astrodynamicists who are primarily interested in velocity vectors. I recalled a rather simple vector representation discussed by Brand[14] which appeared ideal for my purposes and I developed it as the basic mathematical tool for my study. This research, together with work in one-way trajectories provided me with considerable analytical power which could be used to attack more complex problems. I proposed a hypothetical problem which can be stated as follows: Given a launch planet P_o and launch date T_o, calculate the required encounter trajectory at planet P_i such that the resulting gravitational interaction will generate a post encounter trajectory which intercepts planet P_{i+1} where $i = 1,2,3,\ldots,n-1$. The complete trajectory can be described by a sequence $P_o - P_1 - P_2 - \ldots - P_n$, where n is any arbitrarily large integer and where P_i denotes any arbitrary planet. Since no gravitational interaction is required at P_n, it may be taken to be any arbitrary point or object with known ephemeris. The transfer trajectories $P_i - P_{i+1}$ between encounters are to be calculated also. Notice that once the vehicle is launched we have attained the theoretical possibility

of complete, propulsion-free, interplanetary mobility for space travel anywhere in the Solar System. Moreover by choosing the initial conditions to be launch date T_o and time T_1 of closest approach to P_1 along with the profile sequence $P_o - P_1 - P_2 - \ldots - P_n$, it is possible to keep the only required rocket thrust for the initial injection to very low values. I viewed each successive encounter as the fundamental and only vehicle thrust source to be utilized as though it were originating from a powerful on-board rocket engine. Unlike the thrust provided by any on-board rocket engine, these thrust forces increase automatically with vehicle mass as described by the Newtonian equivalence principle. Consequently, once the vehicle is launched, it will not matter if its mass is 10^3 kgm or 10^9 kgm.

I refer to trajectories based upon this design concept as "gravity thrust" trajectories. Other researchers have termed them "swing-by" or "gravity assisted" trajectories. These are rather poor terminologies. Swing-by is too ambiguous and can be confused with any planetary fly-by trajectory such as those of Crocco or the recent Mariner trajectories. Gravity assisted tends to imply that perturbations only assist in achieving interplanetary trajectory changes. The fact, however, is that these required changes are achieved totally by gravitational perturbations. Any reference to assistance should be in connection with the relatively insignificant on-board rocket thrust required

for approach guidance.

The three-body problem was circumvented by assuming that at any given instant one and only one body influences the vehicle's motion. Tisserand's concept of a sphere of gravitational influence[15] supplied the criterion I needed to switch back and forth between the Sun's field and the local field of a near-by planet. A formal JPL technical paper on this concept for interplanetary space travel was written August 1961.[16] In order to discover if the concept was feasible and to identify those profile sequences $P_o - P_1 - P_2 - \ldots - P_n$ which might be useful for actual missions, extensive computer analysis obviously was required. For example, there are 9^n different profile sequences involving n encounters. Unfortunately, the paper received little serious attention, and I was unable to convince Clarke to proceed with the required numerical investigation. However, during this time JPL was intensively involved in the ranger and mariner programs.

Though I returned to UCLA in September, the idea of propulsion-free interplanetary space travel retained its fascination for me. Much work was devoted to constructing various computer flow charts. During the 1961 Christmas vacation I returned to JPL to construct the required computer program. A preliminary program was completed two days after Christmas, and there were high hopes of illustrating the concept with actual trajectory calculations. However, the only computer available was a small

IBM 1620 which I discovered to be orders of magnitude smaller than the size required for the program. With considerable frustration, the program was broken down into several subroutines and run sequentially. One complete trajectory of the form Earth-Venus-Earth was calculated. This was a very tedious process. The computer had to be hand-fed various trial position vectors of the Earth, corresponding to different arrival times. After the trajectory was calculated, a significant difference between the pre-encounter and post-encounter legs was observed. The most important aspect, however, was the fact that the required encounter trajectory had a positive distance of closest approach to the surface of Venus. A negative value would mean that the required distance of closest approach would be less than the planet's own radius. A vehicle on such an encounter trajectory would crash into the planet's surface. This calculation on the small IBM 1620 motivated me to begin a full-scale numerical study on a large computer. I returned to UCLA the beginning of January 1962.

The Los Angeles campus of the University of California was one of the first universities to own and operate an electronic digital computer when the SWAC machine became operational in 1952. By January 1962, the UCLA Computing Facility had a large IBM 7090 computer and was supplying computing services to many universities and colleges in the western United States. This service was

called the Western Data Processing Center. Since computing service was also extended to faculty and graduate students with faculty sponsors, I decided to use it in my numerical trajectory calculations.

My planetary ephemeris[17] was obtained in December 1961 by writing the publisher in London and gave position vectors of all the planets from 1960 through 1980. The month of January was spent punching out these vectors from 1965 through 1980 onto IBM data cards. The purpose here was to put the ephemeris on tape which could be read into the computer's high-speed core memory along with the fortran program. In this way the computer could work on data in its core, thus eliminating time spent reading in various position vectors during the course of computation. A formal application for computing time at the UCLA Computing Facility was submitted at the end of January 1962. Professor Peter Henrichi agreed to act as faculty sponsor and approximately twenty hours computing time under the job entitled "MA11" was received the first week in February.

With the 32,000 word capacity of the IBM 7090's core available, the 1620 program was greatly enlarged and streamlined with enough space left over to accommodate the entire planetary ephemeris. The program required considerable modification and debugging but it was completed by the middle of March. (Except for relatively minor changes in format, this program has remained essentially unchanged in nearly ten years of intermittent operation.)

Unfortunately, by March 1962 I had exhausted most of the twenty hours time allotted me.

I discussed the situation and concept for interplanetary space travel with Frederick Hollander (in charge of computer operations) at the UCLA Computing Facility. Hollander responded by granting me the special privilege of a new job classification without time limitations. He explained that the job would have low priority during daylight hours. However, as soon as the routine work load on the computer fell to a low level, the job would be started and run for as much as several hours without interruption. When a sufficiently great backlog developed (usually around eight or nine each week-day morning), the job would be taken out of core and put onto a special "save tape." When the work load dropped, this save tape would be fed back into the computer's central core. The trajectory calculations would then resume as though there had been no interruption.

Although I was granted essentially unlimited computing time, I had to supply my own output paper. I called Clarke at JPL and made an appointment to see him the following Saturday. At this meeting I also pointed out that I had no way of checking the accuracy of the trajectories, especially the critically important encounter trajectories. Since I did not know that my method of switching between a Sun-centered gravity field and a planet-centered gravity field could be accomplished without

causing major trajectory errors, a check was imperative. Clarke described a sophisticated JPL trajectory integrating program which could be used to check the trajectories. If I could supply certain quantities called B·T and B·R which characterized an encounter trajectory at P_i for a certain time of closest approach, the program would begin a step-by-step numerical integration to calculate the resulting miss vector at P_{i+1}. This miss vector would then be utilized to modify the initial values of B·T and B·R such that a second integration will produce a second miss vector smaller in magnitude than the original. This iteration process is repeated until a miss vector is obtained which is smaller in magnitude than some predetermined ϵ. The integration takes into account all major bodies in the Solar System which act simultaneously on the vehicle. However, this program was extremely unstable in that unless the initial values of B·T and B·R were very close to the correct values, the iterations would fail to converge. I left JPL that afternoon with three boxes of output paper and a proposed formal contract between JPL and the UCLA Computing Facility stating that JPL would supply CF09 (my new special job number) with all the computer paper I needed. Thus began a most unusual relationship between myself, JPL and the University of California which lasted up to September 1964.

On April 17, 1962, I received a letter from JPL describing how the encounter quantitites B·T and B·R are

defined in preparation for the test runs at JPL. In the meantime I had been meticulously checking and rechecking all formulas and equations together with the corresponding fortran computer program. I also explored a few possible trajectory profiles involving three encounters which could be used for the JPL trajectory tests. I prepared two trajectories of the form Earth-Venus-Mars-Earth with different launch and encounter dates. From the generality of the program I knew that if these trajectories were correct, then all others would probably be correct also. The actual tests were performed at the end of April and the results exceeded all optimistic expectations. Rapid convergence resulted and the trajectories were nearly identical with those which would result if all major bodies acted on the vehicle simultaneously throughout the entire flight. Significant trajectory changes occurred between encounters, and the required encounter trajectories which generated these changes had positive distances of closest approach. The discovery of this particular class of gravity thrust trajectories (not to be confused with the constant elliptical paths of Hohmann and Crocco) represented a major breakthrough in the design of round-trip trajectories to Mars.[18] It might be of interest to note that in one sense, a combination of my program with the JPL integration-iteration program represented an actual numerical solution to the n-body problem as it applies to space vehicles moving in our Solar System.

The tests at JPL confirmed the feasibility and basic correctness of this concept for trajectory design.

Consequently, at the beginning of May increasing attention was focused on the question of practicality. Since the ephemeris did not extend past 1980, I decided to concentrate on the decade 1965-1975.

One of the example trajectory profiles I gave in my original paper[16] contained a somewhat arbitrarily selected sequence of inner and outer planets involving eight encounters. In particular it had the form Earth-Venus-Mars-Earth-Saturn-Pluto-Jupiter-Earth. In preparing for actual numerical computations it is essential to have some general information concerning the relative geometrical positions of the planets for various years to act as a guide in selecting reasonable profile sequences. Thus, I drew diagrams of the entire Solar System corresponding to the positions of the planets on January 1 for each year beginning 1965 through 1981. Profiles involving the outer planets such as Earth-Jupiter-P_2-P_3-...-P_n (where P_i denotes an outer planet) proved to be impractical after 1966 or before 1976. However, several test trajectories of the form Earth-Jupiter-Uranus, corresponding to the 1965 Earth-Jupiter launch window and several of the form Earth-Jupiter-Saturn for the 1976 window were calculated. Although the results were spectacular compared to any direct flight Earth-Uranus or Earth-Saturn trajectories, any complete numerical analysis of these or other profiles involving many outer planet encounters required an expanded planetary ephemeris extending (if possible) to

the year 2000. This was a rather serious disappointment since my concept for space travel in the outer Solar System required the large perturbations which could only be obtained from outer planets. In particular the tremendous perturbation available from Jupiter made it clear that this planet would be the key to missions to every other outer planet or for that matter, to any place in the entire Solar System.

I began a systematic search for trajectory profiles of the form Earth-Mars-Jupiter, Earth-Venus-Jupiter, Earth-Mars-Earth-Jupiter, Earth-Venus-Earth-Jupiter, Earth-Venus-Earth-Mars-Jupiter, and Earth-Mars-Earth-Venus-Jupiter. The purpose, of course, was to replace the Earth-Jupiter transfer requiring relatively high launch energies with indirect routes commencing with near minimum energy Earth-Venus or Earth-Mars initial transfers. Such indirect routes could lower the direct transfer minimum injection energies required to reach Jupiter by as much as 400 percent. This search was continued for approximately three months, but no realizable trajectories with positive distances of closest approach were found.

One particular profile possibility which caught my attention in March 1962 was of the form Earth-Jupiter-Saturn-Uranus-Neptune corresponding to Earth-Jupiter 1977-1981 launch windows. Consequently when an expanded ephermeris was obtained, a search was begun for profiles of the form Earth-P_1-P_2-P_3-Jupiter-Saturn-Uranus-Neptune where P_1, P_2

and P_3 were inner planets. By varying Earth-Venus initial transfers from their minimum energies I was able to determine physically realizable trajectories of the form Earth-Venus-Mars-Earth-Jupiter-Saturn-Uranus-Neptune with positive distances of closest approach.[19] This offered the possibility of launching one space vehicle on a "Grand Tour" gravity thrust trajectory which would enable it to visit all planets in the Solar System except Mercury and Pluto. The required injection energies were about 165 percent lower than the minimum required for direct Earth-Jupiter transfers.

At about the time the search for gravity thrust trajectories to Jupiter was begun, I discovered that both Mercury and Mars could be reached via profiles of the form Earth-Venus-Mercury and Earth-Venus-Mars. The initial Earth-Venus transfers were essentially minimum energy. These profiles offered the possibilities of reaching Mercury with less than half the previously assumed minimum energies and doubling the previously assumed opportunities when missions to Mars are possible. In view of the ephemeris limitations, I decided to postpone a detailed numerical analysis of outer planet profiles and begin an extensive analysis of profiles connecting the inner planets.

It soon became evident that the computational research required more IBM 7090s. This problem was solved

in June 1962, when I returned to JPL. Two additional IBM 7090s were placed at my disposal (on a time available basis) and a massive computational effort was initiated to identify all launch periods and minimum energy trajectories contained in these periods (separated by two-day launch intervals) for all profiles of the form Earth-Venus-Earth, Earth-Venus-Mercury, Earth-Venus-Mars, Earth-Mars-Earth and Earth-Venus-Mars-Earth from 1965 through 1974.

By June 1962 I had become sufficiently acquainted with the IBM 7090 system to run it myself. Hence, as soon as a time slot of several hours duration became available (usually around eleven or twelve o'clock midnight) a regular JPL operator would notify me and leave. I recall one particular time quite vividly. It began on the night of July 22, 1962 in a conference room at JPL. A loudspeaker had been set up to monitor communications between JPL and the launch control center for the benefit of JPL employees wishing to follow the Mariner I countdown. A message had just been received indicating that the spacecraft failed to achieve its parking orbit. Although I was hoping for a successful mission I was not as disappointed as most. That unfortunate failure immediately presented the possibility of using two finely tuned IBM 7090s for my gravity thrust trajectory calculations. I began computing on one of the machines forty minutes after the loss of Mariner I. This was the beginning of my longest uninterrupted computation periods. It lasted thirty-seven

hours.

The launch of Mariner II several days later was highly successful and the JPL computers were occupied with telemetry analysis and orbit determination for about a week. After eight days tracking, a fairly accurate preliminary orbit was established. The time of closest approach to Venus was calculated to be December 14, 1962, 1700 hours GMT. Using this data as input to my program, I calculated all encounter trajectories required at Venus to achieve Earth-Venus-Mercury, Earth-Venus-Mars, and Earth-Venus-Earth trajectories. The first encounter trajectory required a negative distance of closest approach but the second and third were positive. I revealed this information to the Mariner II trajectory guidance group and supplied the required B·T and B·Rs. The possibility was discussed at a meeting, but rejected. Thus, from an engineering point of view the first interplanetary gravity thrust mission could have taken place eleven years before what will turn out to be the first such mission--Earth-Venus-Mercury 1973. It should be emphasized, however, that post-encounter trajectories $P_i - P_{i+1}$ are extremely sensitive to errors in B·T and B·R at P_i. Errors of only a few kilometers in these quantities will result in missing P_{i+1} by hundreds of thousands or even millions of kilometers. In 1962 the accuracy capability of the pre-encounter mid-course correction required to achieve these gravity thrust trajectories either did not exist or

was very marginable.

In September 1962, I returned to UCLA to begin my fourth year of graduate studies, however, I still continued my research at JPL. By the middle of November, I had compiled all the numerical results I decided to report in my second JPL paper which was completed in December.[20] (This paper was basically identical to the JPL Technical Report which came out several months later.[21]) Between February 1962 and November 1962 my computations at the UCLA Computing Facility alone totalled over 200 hours. The University's early recognition of the importance of my still theoretical concept for interplanetary space travel and my use of their computing facility moved me to offer a research paper to the first meeting of the Graduate Academy of the University of California. My paper was accepted, and I was selected to represent the UCLA campus.[22]

One month after the University of California's graduate conference I participated in the AIAA Thirteenth Western Region Student Conference in Los Angeles representing UCLA. The University conference was designed as a gathering of advanced graduate students from the several campuses of the University of California who had the good fortune of distinguishing themselves in original research. The AIAA conference, however, was a competition type meeting based upon individual research. There were three levels of competition; undergraduate, masters and Ph.D. I decided to open my presentation at the AIAA conference

by rather boldly asserting that "the concept I am about to describe will revolutionize interplanetary space travel." My presentation and paper won first place in the Ph.D. category.

The winning Ph.D. category papers of each of the four regions all compete in the finals for the national first place award. I was confident that I would win the award easily and my colleagues at JPL were wondering when I was leaving for Washington to pick it up. The last correspondence I had with a representative of the AIAA concerning this matter was dated June 13, 1963. One year later I discovered that the paper had been reclassified as being a Master's paper and ineligible for any national award.[23] Moreover, the paper contained an edited reference to an imaginary Master's thesis which I was supposed to have written. Since I have never been on any masters program at the University I have often wondered whether this incident represented simple mediocrity or calculated interference.

After completing my second paper in December 1962, I took up the problem of determining encounter trajectories which would extrimize the post-encounter trajectory's distance from the Sun and distance out of the ecliptic plane. These trajectories would be valuable for probing the environmental conditions of the entire Solar System. Such trajectories would be extremely difficult to achieve by a direct launch from Earth.[10] I devised an analytic

method to obtain these various post-encounter trajectories from a single pre-encounter Earth - P_1 initial transfer. I constructed the corresponding program for this analysis and started computations in March 1963. In this analysis the solutions corresponded to various zeros of a rather complicated function. I met considerable difficulty in the numerical determination of these zeros and decided to abandon the program (April 1963) until a more suitable analytic solution could be developed. The question of guidance captured my attention at about this time and I developed a general non-linear method to calculate any required velocity correction prior to encounter which would generate the desired post-encounter trajectory.[24]

In June 1963, I attended an AAS symposium in Denver, Colorado, on the "Exploration of Mars." I was keenly interested in applying my concepts of trajectory design to the problem of minimizing energy requirements for manned landing and exploration missions to Mars. In July 1962, I had, in fact, developed a complete mission profile requiring about one-third the previously assumed minimum values.[20] I went to the meeting with the possibility of obtaining a large forum where I could describe my concept of space travel and illustrate how it could be applied to achieve significant energy reductions in almost all interplanetary missions, particularly the manned Mars exploration mission. A review of some of the papers indicated that a landing on the surface of Mars could be

accomplished with almost total atmospheric breaking.[25] After determining the effect this would have on the mission profile I designed for 1972, I saw that it might be possible to carry out the mission with only two ordinary non-nuclear Saturn V launch vehicles.

Instead of attempting to address the symposium, I decided to approach someone personally whom I felt was capable of grasping the full significance of my trajectory designs. Moreover, I wanted a person close to the center of power (i.e., President Kennedy and various NASA heads) who could focus attention on them, and hopefully become involved in their implementation. I listened with great interest to comments made by Maxwell Hunter II during a panel discussion near the end of the symposium. He was then a member of President Kennedy's National Aeronautics and Space Council and therefore a logical person for me to approach. I was impressed with his forward-looking comments and optimistic attitude. Immediately after the panel was adjourned I asked him if he would examine a copy of my March 1963 paper concerning new concepts in space travel. Although I had several copies with me at the meeting, I wanted to include the rough calculations I had made in my hotel room the previous night regarding the Saturn V possibility. I sent Hunter the revised paper about two weeks after our Denver meeting.

As I expected, Hunter readily understood my ideas and was extremely interested. Two months later he produced

a paper[26] describing the concept and its implications for unmanned interplanetary exploration. Although the paper was based almost entirely on my concept of gravity thrust, I was nonetheless disappointed. I had hoped he would concentrate on the new possibilities for manned reconnaissance missions to Venus and Mars in 1970 and 1972, or on the manned Mars Saturn V landing possibility. At that time I felt that this was the most important technical area to be studied.[27] Final plans were being drawn for the huge Nova launch vehicle and accurate velocity requirements for various interplanetary missions to be flown with this vehicle were of utmost importance.

In September 1963, I returned to UCLA with the intention of taking my degree as soon as possible. Kennedy's assassination on November 22 came as a tremendous shock. I found a distinct analogy between his statement concerning "setting sail into outer space" and my concept of gravity thrust.

During the early months of 1964 I found that I could not maintain sufficient detachment from trajectory research to permit a successful completion of my Ph.D. program by June. I occupied most of my time with revising analytic solutions for extremizing post-encounter energy and distance from the ecliptic plane and writing the corresponding fortran computer programs. By this time UCLA and JPL had new IBM 7094 computers which were approximately three times faster than the older 7090 models.

Both of these computing facilities continued to place their machines at my disposal and my second systematic numerical investigation began in April 1964. Since the extremal trajectories did not require any planetary intercept after the first encounter, they could be designed for any Earth - P_1 launch period. I analyzed cases where P_1 was Venus, Mars and Jupiter. Thus, since my ephemeris ended in 1980 I was able to cover the years 1967 through 1978. This paper was completed October 1964.[28]

It might be of interest to note that at this time JPL had three planetary ephemeris tapes covering the years 1950 through 2000. These tapes contained not only position vectors, but also large quantities of related data (first differences, second differences, velocity vectors, nutation information, et cetera). Hence, I decided to use these tapes to extend my own special ephemeris tape to the year 2000 and begin the numerical study of gravity thrust missions to the outer planets which I had to postpone in 1962. Being unfamiliar with extracting selected binary information from data tapes, I sought JPL assistance. However, because JPL was heavily committed to present programs, no one could be found to perform this job. This was an especially frustrating experience since it was essentially a repeat of September 1961. But this time there was one important difference--I did not have to establish feasibility or practicality. Therefore, I decided to return to my graduate studies (at the Berkeley Campus of the University

of California) and let JPL do the detailed numerical computations. I had been involved with the development of JPL fortran programs similar to mine since June 1962. (In fact, I gave JPL a fortran listing of my March 1962 program with detailed explanations as to its use in June 1962.) Considerable work had been done on developing their programs by September 1964. Thus, I was not leaving JPL without any means to continue the study. The computer calculations at JPL were resumed without too much delay by Flandro,[29] Kingsland,[30] and Wallace.[31] Numerous other laboratories and research centers have also become involved in gravity thrust trajectory calculations and their applications to mission design. References 32 through 50 describes additional JPL research and work done at other centers.

Conclusion

This then is the behind-the-scenes development of the concept of gravity thrust space flight. In one sense, however, this development is really just beginning. The variation in possible profile sequences is so large and applications so numerous that it will take many years before any significant portion of them is studied or utilized in actual flights. The concept is by no means a temporary substitute for powerful rocket propulsion engines. Indeed, gravity thrust space flight will enable payloads to increase hundreds or even thousands of fold above values which would result by sending these powerful

rockets along conventional trajectories. Ultimately this concept of gravity propulsion could provide the means through which colonization of other planets and moons will be possible.[19]

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