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Abstract

This paper is the second in a series of IAF papers describing the origin of Dr. Michael A. Minovitch's invention of gravity-propelled space travel, his early work in developing it, and how the various NASA gravity-propelled missions originated from it. The first paper, entitled "The Origin of Gravity-Propelled Interplanetary Space Travel" (IAA-90-630), describes the origin of gravity propulsion during the summer of 1961 within the general engineering and theoretical framework of astrodynamics as it existed at that time. This paper covers the period from January 1962 through September 1964 and describes the details of Minovitch's gravity-propulsion research at UCLA and JPL during this time.

Introduction

Prior to 1961, it was taken for granted that the rocket engine, based on the reaction principle, represented the only means for propelling a space vehicle through the Solar System. These engines were primarily liquid rocket engines developed initially by Goddard in the United States and further developed in Germany during World War II at Peenemünde. Access to the planets was therefore restricted by the inherent and well-known velocity limitation of liquid rocket engines. The famous Hohmann trajectory was universally accepted as the minimum-energy and, thus, the optimal path for traveling to the planets. But using this minimum-energy trajectory for traveling to the most distant planets requires unreasonably long trip times (several decades) and high launch energies. Trajectories taking vehicles close to the Sun or out of the ecliptic plane with a high inclination also require very high launch energy. As a result, only a relatively small portion of the Solar System near the ecliptic plane could be explored with space vehicles. It was universally believed that exploration of most of the Solar System would have to wait until more exotic, high specific impulse nuclear rocket propulsion and/or electric propulsion systems were developed. But because of severe technical problems, these advanced systems would become available only in the distant future. Thus, for all practical purposes, at the beginning of the 1960s, interplanetary exploration was limited essentially to Venus and Mars.

In 1961, Dr. Michael A. Minovitch, then a graduate mathematics and physics student from the University of California, Los Angeles (UCLA) working at the Jet Propulsion Laboratory (JPL) as a temporary summer employee with no prior experience in astrodynamics, formulated (on his own initiative) the first numerical solution to the famous unsolved Restricted Three-Body Problem of celestial mechanics, and used this solution to propose a radically new method for propelling a space vehicle through the Solar System without reaction propulsion.[1] The method involved utilizing the gravitational influence of an easy-to-reach nearby planet to catapult a free-fall space vehicle to a more distant planet -- a trip that would ordinarily require substantial rocket propulsion and/or trip time using traditional direct-transfer trajectories. Moreover, Minovitch also recognized that by utilizing a series of such trajectory-changing planetary encounters, it is theoretically possible for a free-fall vehicle to travel to many planets without any onboard rocket propulsion (beyond that required to reach the first planet and to correct for minor trajectory errors). Since technical problems prevented the development of nuclear and electric propulsion, this innovation, which is usually called "gravity-assisted" or "swing-by" trajectories, represented the key propulsion breakthrough that opened the entire Solar System to exploration using relatively small, chemically propelled launch vehicles. The Mariner 10 Earth-Venus-Mercury, the Pioneer 10 and 11, the Voyager 1 and 2, the low launch energy Galileo mission to Jupiter, and the Ulysses mission to the Sun perpendicular to the ecliptic plane were made possible by this innovation.

However, in 1961, many trajectory engineers regarded Minovitch's concept -- space travel around the Solar System without rocket propulsion-- a violation of the law of conservation of energy and dismissed the idea as physically impossible.[1] Minovitch, with a strong background in theoretical physics, knew that the concept was not impossible and in January 1962 began, on his own initiative and independent of JPL, a large-scale research project at UCLA to investigate the practical possibilities.

The propulsion concept Minovitch envisioned involved converting a small fraction of the orbital energies of a series of planets into propulsive thrust for a free-fall space vehicle relative to the Sun by successive Three-Body gravitational interactions. Consequently, unlike reaction propulsion, which required chemical and physical laboratories to develop, Minovitch's concept of "gravity propulsion" required a large computing facility. At that time (January 1962), UCLA was the only university in the western United States that had a large IBM 7090 digital computer (one of the rare "supercomputers" of that era). Minovitch convinced UCLA's Department of Mathematics that his concept of gravity propulsion was theoretically possible, and the Department recommended funding his proposed research project on the UCLA 7090 machine. By early April 1962, the results were so encouraging that the University of California granted Minovitch unlimited computer time on the 7090 machine with greatly increased funding. This was the beginning of one of the most intense computational research projects ever conducted at the

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University of California. In June 1962, Minovitch enlarged his research project to include two more IBM 7090 machines at JPL. This quite unusual relationship between JPL, Minovitch, and UCLA lasted from June 1962 through September 1964 and eventually resulted in all of NASA's gravity-propelled interplanetary missions. It established a new underlying technical methodology for achieving interplanetary space travel throughout the entire Solar System previously believed to be impossible without exotic nuclear and/or electric propulsion.

This paper is the second in a series on the historical development of gravity-propelled space travel. The first paper[1] presented a detailed account of the origin of gravity-propelled space travel within the general engineering and theoretical framework of interplanetary space travel as it existed at that time and covered the period from spring of 1961 through December 1961. This paper covers the two and a half years Dr. Minovitch spent investigating his propulsion concept at UCLA and JPL. It presents a detailed account of this research from January 1962 through September 1964. In some instances events occurring in 1965 are described to continue the historical context of the events in 1964. Numerous references to source material are included to support the text. Direct quotations from Dr. Minovitch are from a series of recorded interviews conducted by Richard Dowling, William Kosmann and Rex Ridenoure during the spring of 1990 in Los Angeles, California.

Minovitch's Gravity-Propulsion Research Project at UCLA

Although numerous books and articles have been written on the effect gravity-propelled space travel had on the history of interplanetary exploration, nothing has ever been published describing the crucial role that UCLA played in this development. To understand this role, it is important to note that UCLA was one of the few research centers that pioneered the early development of high-speed electronic computers and their use in numerical analysis.

The UCLA Computing Facility

During the 1940s and 1950s, UCLA became one of the world's leading research centers for numerical research using high-speed electronic digital computers. During the 1940s, UCLA's prestigious Institute for Numerical Analysis, funded by the National Bureau of Standards, owned and operated one of the few General Electric Differential analyzers.[2,3] With the added support of the U.S. Air Force and U.S. Navy, the Institute expanded its basic research in the design and construction of new high-speed electronic digital computers. This research led to the creation of the SWAC (Standards Western Automatic Computer) machine, which became operational at UCLA in the early 1950s. At the time of its dedication in August 1950, it was the world's fastest electronic digital computer.[4,5]

The Institute was located at the extreme northern part of the UCLA campus. The SWAC computer was housed in a large wooden frame building that also contained a library. This library, which contained some of the most advanced books and journals on mathematics and theoretical physics, was used primarily by researchers using the SWAC computer. Minovitch found this library ideal for his academic studies and used it during the latter part of the 1950s. Although this library was not intended for student use, the librarian recognized Minovitch's attraction to mathematics and physics and let him work there, often after closing hours. The atmosphere in that small one-room library was like that of a monastery.

Although Minovitch's academic interests were in abstract mathematics (primarily differential geometry) and theoretical physics, his proximity to the SWAC computer and the Institute for Numerical Analysis induced him to take formal courses in numerical analysis and in automatic digital computers. These courses, taken in 1957 when he was an undergraduate, introduced Minovitch to numerical methods for solving complex systems of differential equations via integration/iteration techniques. These courses played an important role in his study of the Restricted Three-Body Problem in 1961 in that he recognized that this problem could be solved by these techniques by utilizing a high-speed digital computer if a sufficiently accurate initial approximation could be determined that would converge to the real solution.

Toward the end of the 1950s, a much larger IBM 709 computer was installed. A new research center at UCLA was created around this computer called the Western Data Processing Center (WDPC). It was attached to UCLA's School of Business Administration and functioned as a cooperative data processing research center involving many colleges and universities in the western United States.[6] In 1960, the 709 computer was replaced by what was then the world's most powerful commercial digital computer -- the IBM 7090. This multimillion-dollar computer was so large and required so much air-conditioning that its installation usually required a specially-designed building. It represented a quantum-leap in computer power and was regarded as the "supercomputer" of that era.[7] A special building was constructed at UCLA to house it.

At that time (1960) the Institute for Numerical Analysis became an adjunct of UCLA's Department of Mathematics. However, a separate Department of Computer Sciences was created under the direction of Professor Charles Tompkins. Professor Tompkins, who was a principal member of the Institute for Numerical Analysis, became Director of Numerical Analysis Research at UCLA. The UCLA Computing Facility, also under the overall direction of Professor Tompkins, operated the IBM 7090 computer for WDPC. Actual operational control of the computer was directed by Professor Frederick Hollander.

Initial Research at UCLA

Having failed to interest JPL in his concept of gravity-propelled interplanetary space travel because of a fundamental misunderstanding in the law of conservation of energy, Minovitch decided on his own initiative (without informing JPL) to conduct the numerical investigation of gravity propulsion himself using the UCLA IBM 7090 computer. This decision to pursue research outside his field was carefully considered because, at that time (January 1962), Minovitch was pursuing an extensive series of graduate courses in advanced mathematics and physics.[8] However, his rough slide-rule calculations made during 1961 indicated that the trajectory of a free-fall vehicle relative to the Sun could be radically changed without rocket propulsion by detouring around an intermediate planet that was not the target planet. These slide-rule calculations were directed at determining whether or not the theoretical concept of multiplanet gravity-propelled interplanetary space travel had any chance of being physically realizable taking into consideration the actual mass and radii of the various planets. These calculations indicated that, under certain conditions, the theoretical concept could become physically realizable (i.e., the required distances of closest approach to the planets' centers could be greater than their radii). Therefore, in January 1962, it was apparent to Minovitch that his concept offered the real possibility of exploring the entire Solar System with relatively small launch vehicles using conventional chemical rocket propulsion. This was a significant scientific discovery of major proportions because at that time such a possibility was believed to be an absolute physical impossibility.[1]

The other important consideration that influenced Minovitch's decision to pursue this research was more academic. The engineering feasibility of gravity-propelled interplanetary space travel rested on developing a valid numerical solution to the Restricted Three-Body Problem. But in January 1962, such a solution did not exist and was considered to be one of the most difficult problems of celestial mechanics.[1,9] However, Minovitch knew that his vector methods of finding an approximate solution to this problem that he developed in 1961[1] must be fairly close to the actual solution. Thus, since the differential equations of motion of a body moving through the Solar System under the influence of all the major planets acting simultaneously are known exactly, Minovitch realized that by applying methods of integration/iteration differential corrections, the system of Three-Body Problems could be solved to any accuracy desired. The raw computational power of a high-speed digital computer would make this possible. Each successive critical planetary approach trajectory designed to propel the vehicle to the next planetary intercept could therefore be determined to any desired accuracy. Minovitch wanted to know if this were actually the case. If it were, his work also represented an important contribution to celestial mechanics -- the first numerical solution to the famous unsolved Restricted Three-Body Problem.

For these reasons, Minovitch decided to initiate a numerical investigation of his concept of gravity-propelled space travel at UCLA simultaneously with his formal academic studies. Since this investigation involved the construction of a very large computer program and the numerical processing of this program on a high-speed digital computer, Minovitch had to convince the UCLA Computing Facility of the scientific merit of his concept of gravity-propelled space travel and his proposed research project.

Although it was possible, in principle, for students to gain access to UCLA's 7090 computer, access was not automatic. Students who were granted access were usually conducting research on a dissertation project under the overall direction of a faculty member. The research Minovitch wanted to conduct was not related to any dissertation project and was not known to any faculty member. In fact, it was not even related to his formal academic curriculum. At that time, gravity-propelled space travel (i.e., gravity propulsion) was an entirely new idea in physics, mathematics, and celestial mechanics. There were no "experts" in this field because the field itself did not exist. It was so new that many professional trajectory engineers believed the basic concept itself was a violation of a law of physics.[1]

Minovitch also felt that even if he were granted time on the 7090 computer, it would not be sufficient to conduct the type of investigation he was contemplating. At that time, UCLA was the only university in the western United States that had a large digital computer. WDPC was organized to share this computer with about seventy leading universities and colleges (such as Stanford, Caltech, UC Berkeley, etc.). There were many faculty members and other researchers from each of these universities who had important research projects requiring computer analysis on the UCLA 7090 machine.[6] For example, essentially all computer analysis of nuclear physics experiments conducted by the giant accelerators at the UC Berkeley Lawrence Laboratory was done on the UCLA 7090 computer. Thus, the demand for computer time on the UCLA 7090 was very great. All of this was on Minovitch's mind when he discussed his proposed research project with Frederick Hollander in January 1962.

Hollander expressed sincere interest in and was intrigued with Minovitch's concept of gravity-propelled space travel. Having had some experience in astronomical calculations prior to coming to UCLA, Hollander did not object to Minovitch's idea of propelling a space vehicle from planet to planet around the entire Solar System using the orbital energy of passing planets to effect trajectory changes instead of onboard rocket propulsion. Minovitch also described his efforts to interest JPL in this concept and how it was rejected on fundamental grounds. Trajectory research for space travel was the proper domain for JPL, but Hollander evidently realized that Minovitch's concept of space travel went beyond the standard engineering of trajectory determination and into a new and unfamiliar area intimately connected with the unsolved Three-Body Problem.

Despite his interest, Hollander did not have the mathematical expertise to evaluate the merits of Minovitch's proposed solution.[10] He understood that the propulsion concept Minovitch was proposing was useless without a valid solution to the Restricted Three-Body Problem, but he also knew that no such solution existed. Thus, he was apprehensive about granting Minovitch access to the UCLA 7090 to calculate trajectories that are supposed to be unsolvable (i.e., noncomputable). Hollander knew that there was one applied mathematician, Professor Peter Henrici, in UCLA's Department of Mathematics who was familiar with the Three-Body Problem and qualified to evaluate Minovitch's proposed solution. Hollander told Minovitch that if he could get Henrici to evaluate the basic soundness of his solution and recommend computer time on the 7090 under his sponsorship within the Department of Mathematics, then he (Hollander) would urge the facility director, Dr. Tompkins, to approve Minovitch's application for computer time.

January 1962 Meeting with Professor Peter Henrici

Minovitch understood Hollander's position and the condition he laid down for gaining access to the UCLA 7090 computer. But Minovitch was not comfortable about meeting this condition. The frontiers of scientific research are frequently accompanied with undesirable personal jealousies, egos, and professional rivalries which stem from basic human emotion that can seriously impede scientific progress. If the stakes are high -- if the implications of the scientific discoveries are of a revolutionary nature -- these undesirable human aspects can be intense. Thus, Minovitch was not looking forward to meeting a professor of mathematics who evidently spent part of his professional career working on the unsolved Three-Body Problem (and Poincaré's proof of its analytic insolvability[1]) and essentially telling him that he (Minovitch), a mere graduate student, working in the field for only three weeks, believed that he had developed the first numerical solution for not only this problem, but a much more difficult system of Three-Body Problems.

In contemplating the meeting with Henrici, Minovitch decided to rely on the strength of his mathematical formulation and emphasize the fact that the numerical solution of any system of differential equations could, in principle, be obtained by differential iteration techniques where each iterant is obtained by a detailed numerical integration process. Since Henrici himself taught these techniques in his graduate courses and seminars on the numerical solution of systems of differential equations, and was familiar with the enormous computational power of a high-speed digital computer, Minovitch felt that there was a good chance to win his support. But the crux of the problem was obtaining a system of differential correction integration/iteration processes (with six independent variables) that simultaneously converged to a solution. In the case of the Restricted Three-Body Problem, the initial approximation had to be very close to the actual solution to ensure convergence (see page 4, ref. 1). Minovitch had to convince Henrici that the vector methods he developed during the summer of 1961, incorporating a moving sphere of influence, and his method of decoupling the Three-Body Problem into a system of Two-Body Problems would provide a sufficiently accurate initial approximation that would converge to the exact solution. Minovitch recalls the meeting with Henrici in January 1962 in his office in Royce Hall:

> "Henrici was intrigued with my idea of gravity-propelled space travel from the beginning of our conversation. I described how I invented the concept while working at JPL during the summer of 1961 and showed him a copy of my August 23, 1961 paper [10]. I described my experience with [Victor] Clarke during December 1961 and his rejection of the concept on fundamental grounds. Henrici said that my concept did not violate any law of physics but it required the solution of the unsolved Restricted Three-Body Problem. I described the vector methods I developed for representing conic trajectories in three-dimensional space and how I used these methods, together with Tisserand's sphere of influence, to obtain an approximate solution by patching the asymptotes of each hyperbolic encounter trajectory to the pre-encounter and post-encounter legs to obtain a smooth continuous trajectory from planet to planet around the Solar System from start to finish. I described why conventional rocket-propelled space travel is so difficult by describing the exponential nature of the rocket equation, and how my method of space travel could, by circumventing rocket propulsion, lead to a significant breakthrough in the exploration of the Solar System. I told him I wanted to investigate this problem on the UCLA 7090 because it was not going to be investigated at JPL and because I believed it represented a solution to the unsolved Restricted Three-Body Problem. Without any hesitation, Henrici signed my application for computing time and he wished me good luck with the project. The meeting was over in about fifteen minutes."

Minovitch took the signed application[11] to the UCLA Computing Facility office and Hollander signed it on January 17, 1962. The next day, Minovitch received official notification that his application was approved for 14 hours of 7090 time and was given the project designation MA-11.[12]

Constructing the Computer Program

The research project Minovitch began in January 1962 involved advanced celestial mechanics and applied mathematics. But Minovitch had little expertise in either of these fields. His only experience in FORTRAN programming was a small amount he picked up at JPL during two weeks in December using a very small IBM 1620 computer with the help of Helen Ling (who is still at JPL). But Minovitch was so convinced that he was onto something very important that he simply decided to proceed on a "learn-as-you-go" basis. Thus, he began his research project by enrolling in a one-week accelerated course in FORTRAN programming at WDPC.

One of the most basic and important aspects of his research project would involve calculating accurate planetary position vectors. This required an accurate planetary ephemeris (a numerical table of each planet's position vector over time). Minovitch wanted accuracy in his trajectory calculations because he viewed his analysis as generating actual realizable numerical solutions to the Restricted Three-Body Problem. His propulsion concept could be utilized only if the corresponding N-Body solution trajectories (i.e., the actual trajectories that would result in the real Solar System where all the mass bodies exert gravitational forces on the vehicle simultaneously and continuously) were calculable from his patched-conic approximations. Initially, he planned to accomplish this by calculating the time a vehicle enters a sphere of influence and the corresponding position and velocity vectors. This data would then be sufficient to begin an integration/iteration differential correction process using the differential equations of motion corresponding to all of the major bodies in the Solar System exerting gravitational forces on the vehicle simultaneously that would converge (hopefully) to the exact vectors (approach trajectory) in the real N-Body case that would be required to gravitationally catapult the vehicle to the next planet in the encounter sequence. Finding an initial approximation to these vectors that would converge to the actual N-Body vectors was equilavent to finding a numerical solution to the N-Body Problem. This is what Minovitch believed his patched-conic trajectory calculations would do and why he needed an accurate ephemeris.

During the summer of 1961, Minovitch learned that JPL was using a high-accuracy British planetary ephemeris for all their interplanetary trajectory calculations. This ephemeris was given in a book[13] published in England. Before leaving JPL in September 1961, Minovitch wrote the publisher for a personal copy of this book, which arrived on December 13, 1961. The book listed the heliocentric equatorial coordinates x, y, z of each planet at regular time intervals from 1960 through 1980. After completing the FORTRAN programming course, Minovitch set out to actually keypunch onto data cards the entire planetary ephemeris of all nine planets given in this book. This was a very tedious and difficult process. He had no experience in typing or keypunching, and every number had to be error-free. Each data card had a six digit Julian Date (a numerical equivalent of calendar date), three x, y, z, position coordinates, and an integer n that identified the planet (one through nine). The result was a hand-made planetary ephemeris consisting of about 4,000 data cards. These data cards were transferred onto an input data tape (ephemeris tape) and fed into the 7090 core along with the FORTRAN gravity propulsion computer program. The computer program was designed with a subroutine that would use the planetary ephemeris data to calculate the position and velocity vectors of any planet at any time between 1960 and 1980. It took Minovitch approximately two weeks of keypunching to construct this ephemeris.

The vector techniques Minovitch developed for solving the Restricted Three-Body Problem were based upon representing a conic trajectory in three-dimensional space by two orthogonal vectors $\vec{e}$ and $\vec{h}$ instead of the usual six orbital element scalar representation. The details are given in his 1961 paper.[10] However, that paper used a complicated method for calculating the $\vec{e}$ vector of a trajectory passing between two given position vectors $\vec{R}_1$ and $\vec{R}_2$ corresponding to possible interplanetary legs. Shortly after that 1961 paper was written, Minovitch developed a simple equation to calculate the $\vec{e}$ vector from a linear combination of $\vec{R}_1$ and $\vec{R}_2$ with some auxiliary equations for determining the scalar coefficients ($\vec{e} = \alpha\vec{R}_1 + \beta\vec{R}_2$). This formulation made the analysis more elegant and was incorporated into the FORTRAN program. The basic computer code that he developed for the program closely followed his 1961 paper.[10]

The computer program[14] was designed to calculate gravity-propelled interplanetary trajectory profiles of the general form $P_0 - P_1 - P_2 - \ldots - P_n$ $(2 \leq n \leq 9)$ where P_0 denotes the launch planet. Any planet P_i $(i = 1, 2, \ldots, n)$ in any encounter sequence could be any of the nine planets in the Solar System, Mercury to Pluto. The number of different planetary encounter sequences in a two-planet, gravity-propelled trajectory $P_0 - P_1 - P_2$ is equal to $9^3 = 9 \times 9 \times 9 = 729$. There are 9^{10} different planetary encounter sequences for gravity-propelled trajectories having nine planetary encounters $P_0 - P_1 - P_2 - \ldots - P_9$. Thus, the computer program was capable of determining a total of $9^3 + 9^4 + \ldots + 9^{10} = 3{,}922{,}633{,}349$ different gravity-propelled trajectory profiles (having launch and encounter dates within the 1960-1980 planetary ephemeris).

Fig. 1 is a reproduction of the first two pages of Minovitch's UCLA 7090 gravity-propelled multiplanet trajectory program. The trajectory profile matrix NP(I,J) defined the planetary encounter sequence for the J'th mission. For example, if the trajectory profile of the third mission were Earth-Venus-Mars-Jupiter-Saturn-Pluto, the third row vector of the mission matrix input data would be NP(I,3) = (3,2,4,5,6,9), where the planets are represented by the usual integers 1 through 9. The program had the capability of analyzing up to ten different trajectory profiles for each run (J = 1 to 10).

The underlying principle of gravity-propelled interplanetary space travel involves launching a vehicle to the first planet P_1 with low launch energy via conventional rocket propulsion and then propelling the vehicle around the Solar System without rocket propulsion via the gravitational forces generated by each successive planetary encounter. Thus, the launch dates T_0 must be confined to the various launch windows for conventional transfer $P_0 - P_1$ trajectories which represent the first leg of gravity-propelled multiplanet trajectories. In January 1962, Minovitch did not know where these various launch windows were during the twenty-year 1960-1980 time period. Therefore, he also constructed a separate direct-transfer trajectory computer program to determine these launch windows.

The general methodology Minovitch initially planned for his research project involved first determining the various $P_0 - P_1$ launch windows via the direct-transfer program and then sweeeping through each $P_0 - P_1$ launch window with the more complicated gravity-propelled computer program to investigate various gravity-propelled trajectories of the general form $P_0 - P_2 - \ldots P_n$ where $2 \leq n \leq 9$. But there was one important aspect in this plan that was completely unknown to Minovitch. Since he had no previous programming experience with the 7090 machine, he had no idea how long it would take to compute a gravity-propelled trajectory assuming that the program worked properly (without hanging-up in any infinite loop). For example, he didn't know whether it would require 3 seconds, 30 seconds, or 300 seconds to calculate an n = 3 type trajectory. If the calculation took a long time, the time required to conduct even a rough numerical investigation would be astronomical due to the vast number of possible encounter sequences. He concluded that it would be prudent to devise a method whereby planetary encounter sequences could be inspected visually before any extensive numerical computations were made. Those encounter sequences that appeared to require negative distances of closest approach were eliminated from the numerical investigation. Consequently, Minovitch constructed a large collection of diagrams illustrating relative planetary positions corresponding to each year from 1965 to 1980.[15] Trajectory profiles with planetary encounter sequences requiring retrograde

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MA11D

C       TEST PROGRAM FOR THE DETERMINATION OF INTERPLANETARY ROUND TRIP
C                         TRAJECTORIES FOR FREE FALL SPACE VEHICLES
      1 FORMAT(F7.1,F9.6,F11.6,F11.6,F11.8,E14.6,F9.6)
      2 FORMAT(6E12.6)
      3 FORMAT(F6.0,9F7.0)
      4 FORMAT(F6.2,9F7.2)
      5 FORMAT(E6.1,4E8.1)
    515 FORMAT(E12.7,3E14.7)
      6 FORMAT(I2)
      7 FORMAT(10I5)
      8 FORMAT(1H1,80H                                              THIS IS REC
     1ONNAISSANCE MISSION NUMBER  I2)
      9 FORMAT(1H )
     10 FORMAT(35H TRAJECTORY PARAMETERS FOR MISSION  I3,26H CORRESPONDING
     1 TO LAUNCH =  F9.3,33H AND FIRST PLANETARY INTERCEPT =  F9.3)
     11 FORMAT(1H ,F9.3,F13.6,2F11.6,F14.3,F10.3,F16.3,F13.6,2F11.6)
     12 FORMAT(1H ,F8.3,F9.3,E14.5,E12.5,E14.5,2E12.5,E14.5,2E12.5)
     13 FORMAT(32H DISTANCE OF CLOSEST APPROACH =  F10.2,32H VELOCITY AT C
     1LOSEST APPROACH =  F7.3,30H ENERGY AT CLOSEST APPROACH =  F8.3)
     14 FORMAT(60H                                    ASYMPTOTIC LAUNCH VECT
     1OR =  3E15.6)
     15 FORMAT(28H           INJECTION ENERGY =  F8.3,31H          INJECTION
     1 VELOCITY =  F6.3,30H          TOTAL FLIGHT TIME =  F8.3)
     16 FORMAT(39H TRAJECTORY PARAMETERS FOR LAUNCH DATE  F10.3,13H  OF M
     1ISSION  I2,23H  ARE BEING CALCULATED  )
     17 FORMAT(119H  LAUNCH   INTERCEPT  RETURN    THETA12 THETA23   A12
     1    A23       IE      IV     T(S)      DOCA        VOCA    DA       TT  )
     18 FORMAT(1H ,F9.3,2F10.3,2F8.2,2F9.5,F8.2,F7.2,F7.3,F11.2,F8.2,F7.2,
     1F9.3)
    201 FORMAT(1H0,72H                                                   LAUN
     1CH PLANET = MERCURY  )
    202 FORMAT(1H0,72H                                                   LAUN
     1CH PLANET = VENUS    )
    203 FORMAT(1H0,72H                                                   LAUN
     1CH PLANET = EARTH    )
    204 FORMAT(1H0,72H                                                   LAUN
     1CH PLANET = MARS     )
    205 FORMAT(1H0,72H                                                   LAUN
     1CH PLANET = JUPITER  )
    206 FORMAT(1H0,72H                                                   LAUN
     1CH PLANET = SATURN   )
    207 FORMAT(1H0,72H                                                   LAUN
     1CH PLANET = URANUS   )
    208 FORMAT(1H0,72H                                                   LAUN
     1CH PLANET = NEPTUNE  )
    209 FORMAT(1H0,72H                                                   LAUN
     1CH PLANET = PLUTO    )
    211 FORMAT(1H0,62H
     1  MERCURY  )
    212 FORMAT(1H0,62H
     1  VENUS    )
    213 FORMAT(1H0,62H
     1  EARTH    )
    214 FORMAT(1H0,62H
     1  MARS     )
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MA11D

    215 FORMAT(1H0,62H
     1  JUPITER  )
    216 FORMAT(1H0,62H
     1  SATURN   )
    217 FORMAT(1H0,62H
     1  URANUS   )
    218 FORMAT(1H0,62H
     1  NEPTUNE  )
    219 FORMAT(1H0,62H
     1  PLUTO    )
    221 FORMAT(1H0,72H                                                   ARRI
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    224 FORMAT(1H0,72H                                                   ARRI
     1VAL PLANET = MARS     )
    225 FORMAT(1H0,72H                                                   ARRI
     1VAL PLANET = JUPITER  )
    226 FORMAT(1H0,72H                                                   ARRI
     1VAL PLANET = SATURN   )
    227 FORMAT(1H0,72H                                                   ARRI
     1VAL PLANET = URANUS   )
    228 FORMAT(1H0,72H                                                   ARRI
     1VAL PLANET = NEPTUNE  )
    229 FORMAT(1H0,72H                                                   ARRI
     1VAL PLANET = PLUTO    )
      DIMENSION A(4,517,9)
      DIMENSION G(7,9)
      DIMENSION EX(9),EY(9),EZ(9),HX(9),HY(9),HZ(9)
      DIMENSION NP(10,10)
      DIMENSION TCA(10),BLI(10),TL(10,10),ELI(10),TL1(10,10),NNM(10)
      DIMENSION PP(10),PPX(10),PPY(10),PPZ(10)
      DIMENSION VPX(10),VPY(10),VPZ(10)
      DIMENSION EA(10),EE(10),EL(10),EH(10),THETA(10)
      DIMENSION EHX(10),EHY(10),EHZ(10),EEX(10),EEY(10),EEZ(10)
      DIMENSION VLX(10),VLY(10),VLZ(10),VAX(10),VAY(10),VAZ(10)
      DIMENSION V1LX(10),V1LY(10),V1LZ(10),V1AX(10),V1AY(10),V1AZ(10)
      DIMENSION V1LS(10),V1AS(10),C3L(10),C3A(10),VAS(10),VLS(10)
      DIMENSION D(3),B(3),E(3),V1AVS(10),V1A(10),V1L(10),CSOL(10),TT(3)
      DIMENSION V1LU1(10),V1LU2(10),V1AU1(10),V1AU2(10),TI4(10)
      DIMENSION HA(10),HE(10),HH(10),DOCA(10),TINS(10),TOT(10)
      DIMENSION TI3(10),TIM(10),DEFA(10),NPM(10),NA(10,10),NL(10)
      DIMENSION HEX(10),HEY(10),HEZ(10),HHX(10),HHY(10),HHZ(10)
      DIMENSION R1AX(10),R1AY(10),R1AZ(10),R1LX(10),R1LY(10),R1LZ(10)
      DIMENSION TS(2,10),PPS(2,10),RSX(2,10),RSY(2,10),RSZ(2,10)
      DIMENSION TTIP(10),ALTINJ(10),TI(10),TIO(10),DTD(10)
      DIMENSION C3CA(10),V1CA(10),V1CAU1(10),V1CAU2(10)
      DIMENSION RAX(10),RAY(10),RAZ(10),RLX(10),RLY(10),RLZ(10)
      READ INPUT TAPE 5,1,((G(I,J),I=1,7),J=1,9)
      DO 20 K=1,9
   20 READ INPUT TAPE 5,2,EX(K),EY(K),EZ(K),HX(K),HY(K),HZ(K)
      READ INPUT TAPE 5,3,(BL1(M),M=1,10)
      READ INPUT TAPE 5,4,(TI3(M),M=1,10)
      READ INPUT TAPE 5,4,(TI(M),M=1,10)
```

Fig. 1 Reproduction of the first two pages of Minovitch's UCLA gravity-propelled 7090 FORTRAN computer program. The input mission matrix NP(10,10) defined the planetary encounter sequences. Listing made March 1962, Research Project MA-11, UCLA Computing Facility.

post-encounter legs $P_i - P_{i+1}$ were identified from these diagrams and eliminated from the numerical investigation.

With the aid of his diagrams, Minovitch identified approximately 200 different planetary encounter sequences that appeared to be good candidates for realizable gravity-propelled multiplanet trajectory profiles. Among those 200 candidates were Earth-Venus-Mercury trajectories (one of which was used in the Mariner 10 mission); Earth-Venus-Mars trajectories; Earth-Venus-Mars-Earth trajectories (which became known as the "Venus swingby mode" for round-trip missions to Mars); Earth-Jupiter-P_2 trajectories where P_2 = Saturn, Uranus, Neptune, or Pluto (which were used in the Pioneer and Voyager 1 missions); Earth-Jupiter-Saturn-Uranus-Neptune trajectories (one of which was used by Voyager 2); and many other gravity-propelled trajectory profiles.

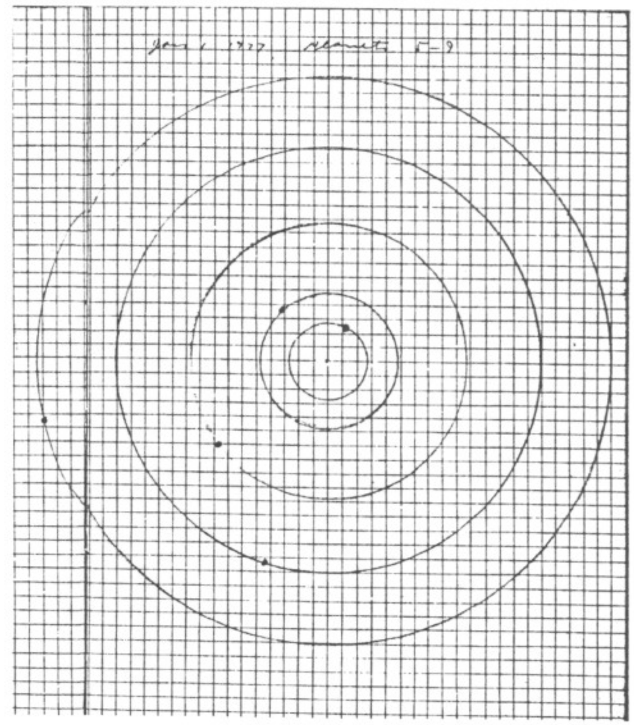


Fig. 2 Reproduction from one page of Minovitch's 1962 UCLA research notebooks showing the relative positions of the outer planets on January 1, 1977 which he used for visually identifying possible gravity-propelled multiplanet encounter sequences prior to the numerical investigation. The heavy dots indicate the planetary positions of Jupiter, Saturn, Uranus, Neptune and Pluto moving in their respective orbits.

Fig. 2, taken from a page of one of Minovitch's UCLA research notebooks, illustrates the relative positions of the outer planets corresponding to January 1, 1977.[15] A Total of 34 such diagrams were constructed (17 involving the inner planets and 17 involving the outer planets). Fig. 3, another reproduction from the same notebook, shows a portion of the numerous planetary encounter sequences for gravity-propelled multiplanet trajectories that appeared to be reasonable based on the planetary configuration diagrams.[15] Those sequences that appeared to be realizable (having positive distances of closest approach) were identified with stars (*). The particular planetary encounter sequence described by the series 3-5-6-7-8 corresponds to the Voyager 2 mission launched in 1977. The diagrams and the possible planetary encounter sequences identified therefrom were constructed during February 1962, prior to the numerical investigation.

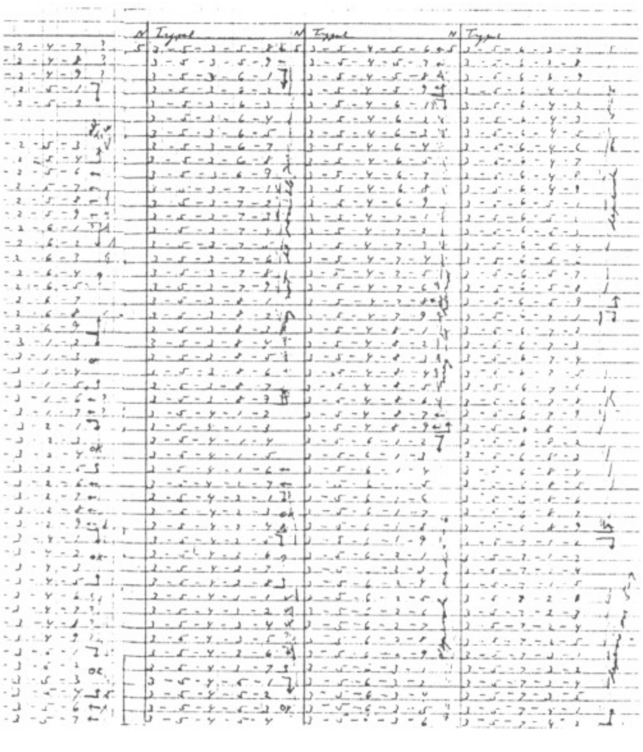


Fig. 3 Reproduction from the same notebook shown in Fig. 2 illustrating a small fraction of the numerous planetary encounter sequences for gravity-propelled space travel. Minovitch identified those sequences from the planetary configuration diagrams that appeared to be realizable (having positive distances of closest approach) with stars (*). Minovitch identified approximately 200 possible encounter sequences in February 1962.

Constructing the gravity-propelled trajectory program was very difficult because of its size and complexity. At that time, the average FORTRAN program constructed by beginning programmers was about 20 to 50 lines long. Minovitch's program was about 1,000 lines long with many branching subroutines. The process of getting the program running on the computer and "debugging" it took several weeks. The standard procedure involved submitting one run at WDPC with a maximum time limit of about ten minutes and studying the results the next day. Corrections would be made and the program would be resubmitted for another run. This one-test-run-per-day process was too time consuming for Minovitch, so in addition to these regular one-a-day runs, he took advantage of a special one-hour time slot between 12 midnight and 1:00 AM during which time more than one run was allowed. Thus, by using this time period, three or four test runs could be made each night in addition to the regular daytime runs. But these night test runs were limited to only five minutes of computer time. Unfortunately, Minovitch's program was so large that the various FORTRAN system compilers used by the 7090 for transforming the program's FORTRAN code into machine language for execution required almost five minutes. Consequently, every time Minovitch submitted his program for debugging, nearly five minutes of valuable 7090 computer time was expended on FORTRAN compiling before any program execution was reached. This was very frustrating because program execution during these test runs was essential to check various parts of the program.

One particulary vexing problem that caused the program to hang-up in an infinite loop for no apparent reason was due to round-off errors. At that time, the IBM 7090 performed numerical calculations with seven-digit accuracy, but the accumulated effect of round-off errors introduced unexpected numerical instabilities that were difficult to identify. These problems were not very well understood in the basic design of digital computers at that time and very little literature was written about it. Since the computer's arithmetic operations were supposed to operate with an accuracy of seven significant digits, Minovitch assumed that he could obtain this accuracy in solving the various equations. In practice, however, only six figure accuracy could be obtained. It took a long time to understand this problem and to build the necessary logic to avoid infinite loops caused by round-off errors. Since Minovitch required the highest possible accuracy to obtain converging differential correction iterations for solving the Three-Body Problems, he was pushing the computer to its ultimate operational limits.

All of this work -- including learning FORTRAN programming on the IBM 7090, constructing the direct transfer program, constructing the gravity-propelled trajectory program, constructing the planetary ephemeris, and identifying the 200 possible gravity-propelled trajectory profiles -- consumed approximately two and a half months. (And during this time, Minovitch was simultaneously taking a full load of advanced graduate courses in mathematics and physics.) Unfortunately, at the end of that time, Minovitch had used up nearly all of 14 hours of IBM 7090 computing time that was originally allocated by WDPC to conduct the research under project MA-11.[16] However, many interesting realizable gravity-propelled trajectory profiles were uncovered during this debugging and testing period that he knew would have important consequences for exploring the Solar System. Among these realizable profiles were Earth-Venus-Mercury trajectories; Earth-Venus-Mars trajectories (which had the potential of doubling the frequency of launch windows for missions to Mars); Earth-Venus-Mars-Earth trajectories (which could be used for non-stop manned reconnaissance missions to both Venus and Mars); and Earth-Jupiter-Saturn trajectories.

But in March 1962, Minovitch was primarily concerned with debugging the trajectory programs and eliminating the unexpected infinite loops. These isolated examples of gravity-propelled trajectories had relatively high launch energies. In order to demonstrate that the concept of gravity-propelled interplanetary space travel was not just an interesting theoretical curiosity of celestial billiards, but rather a fundamentally new and powerful propulsion concept that could provide an inexpensive means for exploring the entire Solar System, Minovitch had to find gravity-propelled trajectories with very low launch energies and an abundance of launch windows. However, by this time, he had gained enough experience using the 7090 computer to determine that the numerical computation of each n = 2 type gravity-propelled trajectory corresponding to a given launch date T_0 and time of closest approach T_1 at P_1 would require about 40 to 50 seconds of computing time. (This minimum computing time rapidly increased when n increased because the post-encounter trajectories were not unique for any encounter sequence and initial values for T_0 and T_1). Consequently, this made it impossible to numerically determine the best encounter sequences $P_0 - P_1 - P_2 - . . . . - P_n$ for gravity-propelled trajectories corresponding to each P_0 to P_1 launch window spanning the time period 1965-1980. This situation would require an enormous amount of computing time and an extended planetary ephemeris because multiplanet missions involving the outer planets require trip times of a decade or more.

Increasing Support From UCLA -- Unlimited Computing Time

Near the end of March Minovitch explained to Hollander that he was running out of computing time[16] and requested more time to continue the investigation. He showed Hollander some of the gravity-propelled trajectories he discovered and explained how the existence of these trajectories, and the propulsion concept behind them, altered the prevailing technical principles of interplanetary space travel which were based upon reaction propulsion and Hohmann transfer trajectories believed to be the two unchangeable pillars of interplanetary space travel. More computing time would undoubtedly uncover many more gravity-propelled trajectories. Minovitch described various encounter sequences and the vast number of different encounter sequences that could be used to explore the entire Solar System. The continued computational investigation was important in order to identify those encounter sequences having low launch energy and positive distances of closest approach. Hollander was intrigued with the possibility of exploring many planets in the Solar System with only one vehicle without any rocket propulsion beyond that required to reach the first planet and realized the potential revolutionary impact the concept had for planetary exploration. The possibility that Minovitch had numerically solved the Restricted Three-Body Problem and went on to use his solution to transform the basic theory of rocket-propelled interplanetary space travel into a gravity-propelled multiplanet celestial ballet around the entire Solar System -- using the Solar System's own orbital energy for propulsion -- was evident. Talks with Henrici may have also convinced Hollander that Minovitch may have indeed solved the Restricted Three-Body Problem and, if he did, his concept of gravity-propelled interplanetary space travel would really be possible. Hollander told Minovitch that it might be possible to obtain a special research status usually reserved for UCLA faculty members who needed extensive computer time, but the decision could only be made by the Director of WDPC.

The decision came on April 2, 1962. Minovitch was given a special "stand-by" classification that would enable his programs to be run on a time-available basis, usually late at night. But most importantly, he was given access to the IBM 7090 computer without any time limitations -- a most unusual privilege for a third-year graduate student. Minovitch was also given the unusual privilege of having his name listed as the "principal investigator" -- a title usually reserved for faculty members from UCLA or other universities. The research project was given a Computing Facility identification number, CF - 09.[17] The fact that the UCLA Computing Facility was, at that time, being used by UCLA and 70 other leading universities -- with hundreds of research projects using the same computer -- demonstrates the high regard the facility had for Minovitch's concept of gravity-propelled interplanetary space travel and the numerical investigation of it.

Beginning the Systematic Numerical Investigation At UCLA

Since the number of possible planetary encounter sequences $P_0 - P_1 - P_2 - . . . . - P_n$ is so enormous (nearly four billion) the gravity-propelled trajectory program was designed to numerically analyze up to ten different encounter sequences for each run. Each encounter sequence could begin at any planet P_0 (usually Earth) and could have as many as nine planetary encounters with any of the nine planets in any order. Each encounter sequence covered a given range of launch dates and first planetary encounter dates that spanned a $P_0 - P_1$ launch window identified by the one-way trajectory program. Consequently, if the time increments between successive launch dates T_0 and successive arrival dates T_1 were small (e.g., two days), hundreds of trajectories would be calculated for each encounter sequence. Therefore, the input trajectory profile mission matrix NP(I,J) for each computer run could keep the program running for several hours.

When the research project was given the special CF-09 "stand-by" classification, the program was modified to take advantage of a special feature in the IBM 7090 system that enabled a program to be interruptable. By depressing certain switches on the computer's control console, the entire core could be dumped onto a special "save tape." When the next block of computing time became available, this save tape would be fed back into the computer's core and the computations would continue as though no interruption had occurred. The output data was recorded on two different output tapes printed at the end of each run. One output tape was used for recording only a few key trajectory parameters (such as launch energy, trip times for each leg, distances of closest approach etc.) while the second output tape was used for recording many trajectory parameters such as position and velocity vectors and orbital vectors entering each planetary sphere of influence. These parameters were needed for calculating the exact trajectories via an integration/iteration process corresponding to the real Solar System where the vehicle's motion is influenced by the gravitational fields of many planets acting simultaneously.

The direct-transfer program[18] was designed to calculate transfer trajectories for up to ten different $P_0 - P_1$ profiles (e.g., Earth-Venus, Earth-Mars, Mars-Venus, Earth-Jupiter, etc.) for each run. The input data covered a given range of launch dates and arrival dates for each trajectory profile. The program was designed to determine the launch windows and specific launch dates T_0 and arrival dates T_1 corresponding to the minimum energy trajectories in each window for each profile. This program was also designed to be interruptable.

Meeting With Clarke, April 7, 1962 At JPL

Although Minovitch was given essentially unlimited access to the UCLA 7090 computer, there was a minor problem involving computer paper. Due to a complicated arrangement at UCLA's Computing Facility, the funding for computer paper was separate from that used for operating the computer. The research project did not provide for the paper, which was then $10 per box. Since Minovitch was preparing such a huge computational research project, he decided to investigate the possibility of obtaining this paper from JPL without cost. Shortly after April 2, 1962, he called Victor Clarke (head of JPL's trajectory group[1]), told him about his UCLA research project, and inquired whether JPL could give him some of their computer paper. Clarke was surprised to hear about the UCLA research project but said that JPL could supply the paper. A meeting was arranged which took place at JPL on Saturday afternoon April 7, 1962 in a conference room on the second floor of Building 202. Minovitch recalls this meeting with Clarke:

> "When we met that Saturday afternoon, I described my 7090 gravity-propelled trajectory program that I constructed at UCLA and various technical aspects, such as its versatility in computing a gravity-propelled trajectory profile with any planetary encounter sequence $P_0 - P_1 - P_2 - . . . - P_n$ $(2 \leq n \leq 9)$ and the fact that I had keypunched the entire British planetary ephemeris book [13] onto data cards. At that time JPL was using the same book for their planetary ephemeris because it was then the most accurate planetary ephemeris available. Clarke indicated that JPL might be willing to buy my program and asked me how much money I wanted for it. This question took me somewhat by surprise. Clarke evidently failed to understand that I was conducting a serious and large-scale research project at UCLA on a new concept for propelling a space vehicle around the Solar System -- a concept that I invented at JPL the previous summer, and which he had rejected as violating the law of conservation of energy [1]. Possible monetary gain had no bearing on my motivation for conducting the research. Although I was still a graduate student, I was doing what I devoted my entire life to -- pure scientific research. However, without mentioning it, I also felt that since he was now offering to buy the program, he must have convinced himself since our last meeting in December 1961 that my ideas about space travel did not violate any law of physics. I explained to him that I was not interested in selling the program, but, like any other scientist, I was interested in preserving my claim on the propulsion concept it was based on and recognition for any possible benefits that might result from it. It was implicity clear that in the context of the conversation with Clarke that I would never have any problems regarding propriety. My personal relationship with Clarke was very cordial at that time, so the thought of asking him to sign a formal document describing the circumstances and origin of my concept of space travel and my UCLA research project never entered my mind. At that time, he may have believed that although my propulsion concept might be theoretically possible, it would most likely be an impractical substitute for onboard rocket propulsion, and that the required planetary approach guidance would be impossible to achieve."

The JPL Tests That Confirmed Minovitch's Numerical Solution Of The Unsolved Restricted N-Body Problem Of Celestial Mechanics

There was another reason why Minovitch decided to contact JPL in early April 1962. Before beginning his large-scale research project at UCLA, he wanted to know if his analytical methods really did represent a valid numerical solution to the Restricted Three-Body Problem. At that time, JPL had a high-precision trajectory integrating computer program incorporating the differential equations of motion corresponding to the real Solar System where all of the major bodies influence the motion of a free-fall space vehicle continuously and simultaneously.[19] If the position and velocity vectors of a free-fall vehicle were known at any time, this program was capable of determining its exact position and velocity vectors at any future time by a numerical integration process. Minovitch asked Clarke if this JPL integrating program could be used in a numerical differential correction integration/iteration process to determine whether his gravity-propelled trajectory program was capable of determining sufficiently accurate approximate encounter trajectories that would converge to the exact trajectories required to gravitationally catapult a free-fall vehicle to each successive planet in the encounter sequence. Clarke indicated that this could be done and indicated that Gene Bollman, a JPL trajectory analyst in Clarke's group, could perform the test if Minovitch provided a gravity-propelled sample trajectory.

Minovitch left JPL that Saturday afternoon with three boxes of computer paper and an understanding that JPL would supply his UCLA research project with all the paper he needed. (Many subsequent boxes of computer paper were delivered to WDPC via JPL delivery vans.)

When Minovitch contacted Bollman about the test, Bollman indicated that the actual numerical iteration process would also involve two encounter parameters $(\vec{B}\cdot\vec{T})$ and $(\vec{B}\cdot\vec{R})$ for each planetary encounter.[20] Minovitch modified his program[21] to calculate these parameters and mailed Bollman two gravity-propelled trajectories of the form Earth-Venus-Mars-Earth for the tests. The iteration generated very rapid convergence to the exact trajectories. The tests were a tremendous success.

The exact encounter trajectories would have been impossible to calculate at that time without using Minovitch's conic approximations as a starting point from which to begin the converging integration/iteration process.[9] When Minovitch received the good news from Bollman, he knew that he had in fact developed not only the first numerical solution to the unsolved Restricted Three-Body Problem and the more difficult N-Body Problem, but also a solution to the much more difficult problem of determining gravity-propelled trajectories that would catapult a free-fall space vehicle around the Solar System from one planet to another, having essentially any number of planetary encounters, without any rocket propulsion. (This was a system of N-Body Problems.) The solution represented a significant achievement in celestial mechanics.

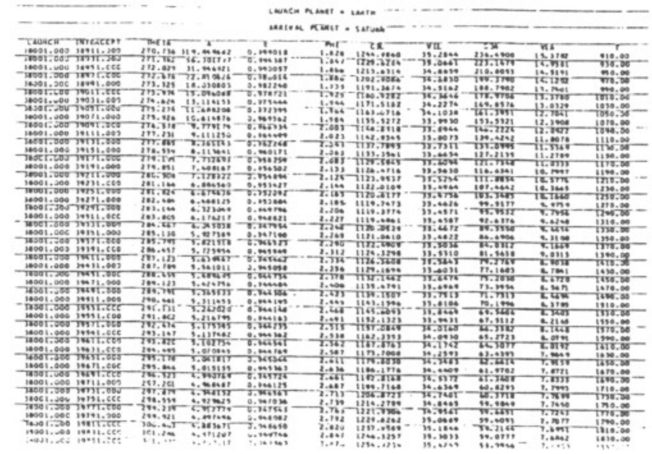
But Minovitch did not publish this historic achievement, nor did he seek any recognition for it. His daily course studies and the ongoing gravity-propulsion research kept him very busy. But he knew that his work had now penetrated the frontiers of a major field of scientific research, celestial mechanics, and that he was working in uncharted territory. Hollander was very pleased to hear about the successful tests and increased the UCLA support by giving Minovitch a room in the WDPC building to use for his research project.

Increasing The Scope Of The Numerical Investigation

After the successful tests at JPL, Minovitch turned his attention to mapping out a long-term systematic numerical investigation of his concept of gravity-propelled interplanetary space travel. He initially confined the numerical investigation to trajectories with launch dates within the 1965-1974 time period in order to uncover those trajectories that could be used for exploring the Solar System in the near term. (This time period was also imposed by the ephemeris limitations which had the effect of making 1980 the upper bound for all planetary encounter dates T_i (see ref. 14). Unfortunately, it was apparent from the planetary configuration diagrams[15] that the most favorable trajectory profiles having multiplanet encounter sequences involving the outer planets (such as Earth-Jupiter-Saturn-Pluto; Earth-Jupiter-Saturn-Uranus-Neptune; etc.) would have launch dates T_0 outside this launch interval [with encounter dates T_i ($i = 1, 2, \cdots n$) beyond 1980] and would require an extended planetary ephemeris. However, this situation did not make it impossible to calculate some trajectory profiles involving the outer planets with the 1960-1980 ephemeris.

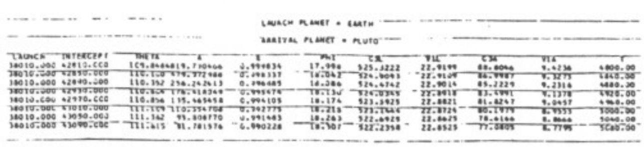
Much of Minovitch's earliest gravity-propelled trajectory calculations involved the outer planets because these planets had the greatest mass and generated the most spectacular gravity-propelled trajectory changes relative to the Sun. In early April, after obtaining unlimited computer time for his research project, he used several hours computing Earth-Jupiter launch windows[22] with his direct-transfer program[18] and used these windows to calculate numerous gravity-propelled multiplanet trajectories of the form Earth-Jupiter-Saturn; Earth-Jupiter-Mercury; Earth-Jupiter-Venus; Earth-Jupiter-Earth; and Earth-Jupiter-Mars. These preliminary computer calculations using Jupiter as the primary propulsion planet were then compared with earlier slide-rule calculations. The determination of distances of closest approach was an important parameter. They were very large, which indicated that Jupiter could be used for obtaining unusual post-encounter trajectories such as solar escape, solar impact, or out-of-ecliptic trajectories previously designed with direct-transfer trajectories.[1,23] But many encounter sequences such as Earth-Jupiter-Uranus or Earth-Jupiter-Saturn-Uranus-Pluto, etc., went beyond the limits of the British ephemeris and produced no numerical results.

Figs. 4 and 5 are reproductions of some of Minovitch's early direct-transfer trajectory calculations to Saturn[24] and Pluto[25] respectively that he made in April 1962 for comparison with gravity-propelled multiplanet trajectories involving the outer planets that ended at these planets (such as Earth-Jupiter-Saturn and Earth-Jupiter- $P_2 - \cdots P_{n-1}$ - Pluto where the intermediate propulsion planets P_i ($i = 2, 3, \cdots, n-1$) = Saturn, Uranus or Neptune). Unfortunately, the encounter dates corresponding to the gravity-propelled multiplanet trajectory profiles to Pluto went beyond the range of the British planetary ephemeris and could not be numerically computed.


LAUNCH PLANET = EARTH
ARRIVAL PLANET = SATURN

LAUNCH	INTERCEPT	THETA	A	E	PHI	C3L	V1L	C3A	V1A	T
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Fig. 4 Reproduction of some of Minovitch's direct-transfer Earth-Saturn trajectory calculations that he used for comparison with Earth-Jupiter-Saturn gravity-propelled trajectories. Listing made April 1962, Research Project CF-09 , UCLA Computing Facility.


LAUNCH PLANET = EARTH
ARRIVAL PLANET = PLUTO

LAUNCH	INTERCEPT	THETA	A	E	PHI	C3L	V1L	C3A	V1A	T
38010.000	42810.000	109.846	4819.770466	0.999834	17.998	525.3222	22.9199	88.8046	9.4236	4800.00
38010.000	42850.000	110.110	479.372988	0.998337	18.042	524.9093	22.9109	86.9987	9.3275	4840.00
38010.000	42890.000	110.352	256.242613	0.996485	18.086	524.4742	22.9014	85.2229	9.2316	4880.00
38010.000	42930.000	110.604	176.418349	0.995474	18.130	524.0345	22.8918	83.4991	9.1378	4920.00
38010.000	42970.000	110.856	135.465458	0.994105	18.174	523.5925	22.8821	81.8247	9.0457	4960.00
38010.000	43010.000	111.109	110.354708	0.992775	18.218	523.1444	22.8724	80.1979	8.9553	5000.00
38010.000	43050.000	111.362	93.808770	0.991483	18.263	522.6929	22.8625	78.6166	8.8666	5040.00
38010.000	43090.000	111.615	81.781976	0.990228	18.307	522.2358	22.8525	77.0805	8.7795	5080.00

Fig. 5 Reproduction of some of Minovitch's direct-transfer Earth-Pluto trajectory calculations that he made for comparison with various Earth - Jupiter - P_i - • • • - Pluto gravity-propelled trajectories. Listing made April 1962, Research Project CF-09 , UCLA Computing Facility.

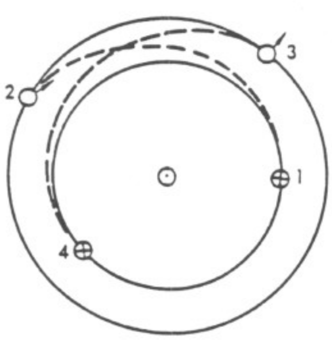
Minovitch did not view this situation as a serious impediment to his overall research project because the Earth-Jupiter launch windows for gravity-propelled multiplanet trajectories involving the outer planets occurred after 1975, which, in 1962, looked a long way off. Most of the real excitement that gripped the world at the dawn of interplanetary space travel sprang from the possibility of a manned landing mission to Mars[26] and that such a mission would discover life on that planet.[27]

Venus And Exploring The Inner Solar System

At the beginning of 1962, serious plans were being proposed for carrying out a manned mission to Mars after the Apollo lunar landing missions.[28] But these plans were all based on classical direct-transfer trajectories, which made manned missions to Mars extremely difficult. For example, if the departing and returning trajectories are based on near-Hohmann minimum energy transfer trajectories, which (on the average) are 258 days long, the required stay-time on Mars before returning to Earth would be about 455 days. This is because the Mars-Earth launch windows occur about 60 days before the Earth-Mars launch windows, and these launch windows are separated by 780-day intervals. This fact was discovered by Hohmann in the mid-1920s and was accepted at the beginning of the 1960s as an unavoidable consequence of basic planetary motion which could not be circumvented. Qutoing directly from page 392 of the famous Willy Ley book[29]: "There is no other way out but to linger on or near Mars until Mars is ahead of the Earth, which means, of course, until the Earth is behind by having completed more than one full revolution around the Sun. This waiting period is unfortunately rather long; it amounts to 455 days. Thus, the round trip to Mars requires 258 + 455 + 258 = 971 days or about two years and eight months."

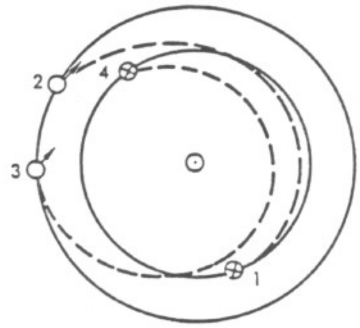
Since manned interplanetary missions this long were believed to be beyond human endurance, the transfer trajectories had to be far from Hohmann with very high launch energies.

Fig. 6 describes the classical manned landing mission to Mars using minimum energy Earth-Mars departing and Mars-Earth returning Hohmann transfer trajectories and illustrates the reason for the long stay-time on Mars. Fig. 7 describes an example of high-energy Earth-Mars and Mars-Earth transfer trajectories used to reduce the total trip time for manned landing missions to Mars. At the beginning of the 1960s, high-energy transfer trajectories were regarded as unavoidable for manned missions to Mars.[30]



1. EARTH DEPARTURE
2. MARS ARRIVAL
3. MARS DEPARTURE
4. EARTH ARRIVAL

Fig. 6 Classical manned landing mission to Mars using Hohmann transfer trajectories illustrating the resulting 455-day stay-over on Mars.



1. EARTH DEPARTURE
2. MARS ARRIVAL
3. MARS DEPARTURE
4. EARTH ARRIVAL

Fig. 7 Example of classical high-energy transfer trajectories used for reducing the total trip times for manned landing missions to Mars.

Since the injection payloads are very high for manned missions to Mars, the launch vehicles required to meet the high-energy requirements of the transfer trajectories were enormous, even when employing high specific impulse nuclear-propelled upper stages. These launch vehicles were called "Super Novas" and "Sea Dragons."[1] The underlying technical methodology behind these designs was based upon meeting the energy requirements by brute force rocket power. Minovitch believed that his concept of gravity propulsion could play a key role in making a manned mission to Mars possible because it had the potential of changing the underlying astrodynamic principles of space travel that made such missions so difficult.

For example, instead of traveling to Mars on the usual direct transfer Hohmann Earth-Mars trajectory, Minovitch believed Mars could be reached via an indirect gravity-propelled trajectory of the form Earth-Venus-Mars where the Earth-Venus leg was a near-minimum-energy Hohmann trajectory. The gravitational field of Venus would then propel the vehicle beyond the Earth's orbit to the orbit of Mars. The vehicle could intercept Mars at a time close to the Mars-Earth launch window for low-energy return trajectories back to Earth. Thus, by employing gravity-propelled trajectories, the traditional 455 day-long waiting period on Mars could be completely eliminated while still employing near-Hohmann minimum-energy launch trajectories -- a feat previously believed to be physically impossible. At that time, the possibility of launching a vehicle to Mars from Earth with an asymptotic velocity relative to the Sun that is less than the Earth's orbital velocity was considered a physical impossibility and was described as such in numerous books and technical articles.[29]

The Earth-Venus-Mars trajectories had the potential of doubling the frequency of launch windows required for traveling to Mars, and Mars-Venus-Earth trajectories had the potential of doubling the frequency of launch windows required for traveling from Mars to Earth. At that time, launch windows corresponding to trips from one planet to another planet were believed to be unchangeable and determined by the relative orbital motion of the launch planet and target planet around the Sun.

At the beginning of 1962 it was generally believed that a manned landing mission to Mars should be preceded by a manned non-stop reconnaissance mission employing a free-fall (ballistic) trajectory. These round-trip trajectories were numerically determined and analyzed in several major studies[31-33] that uncovered the basic characteristics (i.e., launch energies, trip times, launch windows, etc.) needed for mission planning. Battin[31] found that realizable minimum launch energy Earth-Mars-Earth trajectories required total trip times of about 1,100 days (three years) with launch hyperbolic excess velocities v_∞ = 3.87 km/sec. Unfortunately, these trip times were too long for manned missions. At that time it was believed that the only way the trip time could be reduced was by employing higher energy launch trajectories. Johnson and Smith[32] showed that by increasing v_∞ to 8.69 km/sec, the total trip time could be decreased to about 500 days which was believed to be acceptable for manned missions. The results of this research were confirmed by Gedeon.[33] All of these studies took into consideration the gravitational influence of Mars.

In 1956, Crocco[34] discovered an unusual constant elliptical path that would, if it were not for the planetary perturbations, take a free-fall space vehicle from Earth, past the orbits of both Mars and Venus just as these planets arrived, and return it to Earth in a period of exactly one year (see pages 11-12 of ref. 1). Crocco recognized that the gravitational perturbations of Mars and Venus would influence the trajectory. In particular, they would destroy the constant resonant characteristic of the trajectory required to achieve the desired planetary intercepts. To solve this perturbation problem, Crocco used the Venus perturbation to cancel out the effect of the Mars perturbation and therefore obtain a final trajectory very close to his "ideal" unperturbed constant elliptical path.

What was considered to be a crucial ingredient in Crocco's multiplanet trajectory -- which made it realizable -- was the fact that the mass of Venus is considerably larger than the mass of Mars. This made it possible for Crocco to use his underlying analytical design methodology to make the trajectory realizable, i.e., to use the greater perturbational effect of Venus to "correct" the weak disturbing perturbational effect of Mars so that the trajectory would return to Earth. If Venus were intercepted before Mars in the perliminary constant elliptical path, it would be impossible to use the effect of Mars to cancel the disturbing effect of a close passage of Venus to enable the vehicle to return to Earth close to the preliminary constant elliptical path. The corrective power of Mars to obtain realizable round-trip trajectories by utilizing its gravitational influence was known to be fairly weak (see bottom of page 563, ref. 31).

The use of a target planet's gravitational influence to obtain a round-trip free-return trajectory close to a precalculated unperturbed elliptical path was a standard analytical technique at that time even though the actual trajectory could not be determined since it required a numerical solution of the unsolved Restricted Three-Body Problem.[9] Thus, with this underlying analytical framework, Mars had to be intercepted before Venus in round-trip free-fall non-stop multiplanet reconnaissance trajectories. Unfortunately, the required launch hyperbolic excess velocity was 11.70 km/sec.[34] This multiplanet trajectory was also investigated by other researchers who confirmed the basic astrodynamic analysis and characteristics.[35]

The underlying analytical technique in determining round-trip non-stop trajectories (single-planet or multiplanet) close to predetermined constant elliptical paths which was accepted without question, was a result of viewing planetary gravitational perturbations as annoying disturbances that tended to destroy purely Keplerian orbits. This methodology was accepted primarily because perturbations significantly increased the analytical complexity and involved the unsolved Restricted Three-Body Problem.

In early 1962 NASA initiated a study project for early manned exploration missions to Mars.[36] Since Crocco's multiplanet trajectory had a trip time of about one year and required a launch velocity close to the short trip time minimum-energy Earth-Mars-Earth trajectories identified by Johnson and Smith,[32] it was viewed as a prime candidate for a possible precursor reconnaissance mission prior to a landing mission. But the launch velocities were so high that nuclear propulsion was an absolute necessity.[36] This study became known as Project EMPIRE[37] (Early Manned Planetary-Interplanetary Roundtrip Expeditions).

To comprehend how Minovitch's concept of gravity propulsion affected manned interplanetary space travel, it is useful to compare Crocco's constant elliptical path Earth-Mars-Venus-Earth multiplanet trajectory with Minovitch's gravity-propelled Earth-Venus-Mars-Earth trajectory. Although the trip times of the gravity-propelled trajectories are a little longer, the launch energies (v_∞^2, or C_3) are only <u>one-tenth</u> that of Crocco's trajectories.

Gravity propulsion could also be used for significantly reducing the previously believed minimum launch energy required to reach Mercury via traditional direct transfer Earth-Mercury Hohmann trajectories.[38] Minovitch believed that by employing gravity-propelled trajectories of the form Earth-Venus-Mercury, it would be possible to reach Mercury with almost the same minimum launch energy required to reach Venus via Earth-Venus Hohmann trajectories. The Venus encounter could gravitationally decelerate the vehicle several kilometers per second relative to the Sun and reduce the perihelion distance inside the orbit of Mercury. The gravity-propelled trajectory, therefore, had the potential of reducing to <u>one-third</u> the previously believed minimum launch energy required to reach Mercury (i.e., the C_3 launch energy v_∞^2).

It soon became apparent to Minovitch that even the first phase of the research project, involving the inner planets with launch dates in the 1965-1974 time period, would require an enormous computational effort. In less than one month, Minovitch's WDPC office was almost completely full of trajectory computations. He was using special three-ply computer paper because he intended to send one complete set of all gravity-propelled trajectories to NASA Headquarters in Washington, D.C., and another set to JPL. He intended to keep the third set at UCLA where he planned to conduct the analysis. No thought was given to personal financial gain or to obtain funding from NASA to support his UCLA research project. Minovitch knew that his work would revolutionize interplanetary space travel and he wanted to make the results of this work known to

NASA as soon as possible -- by-passing as much bureaucracy as possible.

Discovering Low Launch Energy Gravity-Propelled Trajectories And Changing The Principles Of Interplanetary Space Travel

By the beginning of May, Minovitch had discovered very low launch energy Earth-Venus-Mercury trajectories, Earth-Venus-Mars trajectories, and Earth-Venus-Mars-Earth trajectories. These were tremendously exciting discoveries. He knew that encounters with Jupiter and the other giant outer planets could cause radical trajectory changes relative to the Sun because of their enormous mass. Consequently, finding realizable gravity-propelled trajectories involving these planets would be relatively easy. But at the beginning of the research he did not know, for example, that Venus would have sufficient mass to decelerate a free-fall vehicle coming from Earth on a nearly minimum energy Hohmann Earth-Venus initial transfer trajectory (with a perihelion distance nearly equal to that of Venus' orbit) such that it would lose sufficient orbital energy to intercept Mercury. Nor did he know that Venus could also accelerate a free-fall vehicle arriving on such a low-energy trajectory (with an aphelion distance nearly equal to that of Earth's orbit) such that it would gain sufficient orbital energy to intercept Mars. The distance of closest approach also had to be sufficiently high above Venus' surface such that the passing vehicle would not enter its atmosphere. His rough theoretical slide rule calculations indicated that close Venus passes could generate substantial trajectory changes that would enable a vehicle to intercept Mercury or Mars in certain conditions, but he didn't know how often these conditions would occur or how accurate his slide rule approximations were.

It may be of interest to describe the details of how Minovitch discovered these trajectories. Minovitch recalls the time he discovered very low-launch-energy Earth-Venus-Mercury gravity-propelled trajectories for the 1970 Earth-Venus launch window:

> "By using my direct-transfer interplanetary trajectory program [18], I was able to determine the Earth-Venus launch window by calculating a narrow range of launch dates T_0 and trip times $T_1 - T_0$ such that any Earth-Venus transfer trajectory having these launch dates and trip times would automatically have a low launch energy close to the absolute minimum. I then made another computer run with my gravity-propelled program [21] and restricted the initial Earth-Venus leg of the Earth-Venus-Mercury trajectories to these launch dates and trip times. Consequently, if a realizable gravity-propelled trajectory, with positive distances of closest approach is determined, the trajectory would automatically have very low launch energy. When the computer finds a realizable gravity-propelled trajectory, a large block of detailed trajectory data is recorded onto one of the two output tapes [the main output tape]. This data contained many position and velocity vectors and the complete trajectory parameters ($\vec{e}$ and $\vec{h}$ orbital vectors) corresponding to the heliocentric legs and the critical orbital parameters of the encounter trajectories. It also contained a great deal of other important information, such as distances of closest approach, time in spheres of influence, heliocentric velocity and orbital energy changes, and planetocentric and heliocentric flight path changes (deflection angles), etc., resulting from each planetary encounter. All of this data required several inches of magnetic tape, and when it was recorded, the recording process sounded like a buzzer. When Gordon (the UCLA night shift computer operator) started the gravity-propelled trajectory program at the beginning of the launch window, several minutes went by without any sound from the second output tape drive. I knew this meant the encounter trajectories at Venus required to decelerate the vehicle and send it onto a post-encounter trajectory that would intercept Mercury had negative distances of closest approach and were therefore unrealizable. When a new launch date in the launch window was considered during the computations, the first output tape drive would make a single clicking sound. Since I knew how many different launch dates T_0 would be considered by the computer [because it was part of the input data], I could monitor the progress of the computer calculations through the launch window. After about one-fourth of the way through the computer run, the second data tape moved accompanied by the buzzing sound, indicating that the computer found a realizable low-launch-energy gravity-propelled trajectory and was recorded on the main output tape. About 40 seconds later, the tape moved again, which meant that the computer found another realizable low-launch-energy Earth-Venus-Mercury trajectory corresponding to a slightly different Earth-Venus initial transfer trajectory. I think everyone in that large IBM 7090 computing room at UCLA that night sensed that something important was being calculated, because I was very excited. The main output tape kept moving intermittently at about 40 second intervals for several minutes, so that I knew that dozens of beautiful low launch energy Earth-Venus-Mercury gravity-propelled trajectories were being calculated. After the computer run was completed, I printed the output tapes and became even more excited. Although the initial distances of closest approach were very low (a few kilometers), they increased to over 200 km altitudes -- well outside Venus' atmosphere. I knew that these low launch energy gravity-propelled trajectories to Mercury would some day be used by a reconnaissance vehicle to explore that planet. I did not know when it would happen, but I knew that it would because it represented a means for sending a vehicle

> to Mercury with less than one-third the launch energy that was previously assumed to be the absolute minimum required to reach that planet since the early days of space travel. [See Ref. 38.] The discoveries of low-launch-energy Earth-Venus-Mars and Earth-Venus-Mars-Earth gravity-propelled trajectories occurred in the same way and at about the same time [April - May 1962]. I was then living in a campus dormitory at UCLA Dykstra Hall, so I was able to spend a great deal of time at the UCLA Computing Facility, especially late at night when most of my long computer runs were made."

The Earth-Venus-Mercury mission did take place eleven years later using a relatively small Atlas/Centaur launch vehicle. Known as Mariner 10 Earth-Venus-Mercury, it was NASA's first multiplanet gravity-propelled mission. Each new discovery convinced Minovitch that his concept of gravity-propelled interplanetary space travel would have a major impact on the future exploration of the Solar System, because it would literally change the underlying astrodynamic and propulsion principles.

Using the Computers at JPL

During the meeting with Clarke on April 7, 1962, Minovitch noticed that JPL was installing another IBM 7090 digital computer. He began thinking about the possibility of using the two JPL 7090 computers (on a time-available basis) during the coming summer to accelerate his UCLA research project. Minovitch discussed the possibility with Clarke and other JPL officials, and they said that this would be possible. Since everyone working at JPL must have a supervisor for record purposes, he requested that Dr. William Melbourne be listed as his supervisor when he returned.[39] At that time, Melbourne headed a small group in JPL's Section 312 (Systems Analysis Section) working on low-thrust trajectories for electrically-propelled vehicles[40] and other theoretical projects. (This was the group that Minovitch wanted to join the previous summer.[1]) But neither Melbourne, Clarke, nor anyone else at JPL had any direct connection with Minovitch's research. They were all very busy with their own research projects (NASA research projects) and Minovitch was left on his own to direct and conduct his gravity propulsion research independent of any JPL project. The only reason he returned to JPL that summer was to use their 7090 computers to speed up his ongoing UCLA research project, and almost everyone in the Systems Analysis Section at that time knew it.

Minovitch's research project was very noticeable at JPL in June 1962, and people were literally bumping into it. By May, Minovitch had completely filled his UCLA office with trajectory computations that he stored in many boxes stacked on top of each other on desks and on the floor that nearly reached the ceiling. There was very little room to stand, and sitting down was almost impossible. He called JPL and they sent over a delivery van to pick up the boxes.[41] They were delivered to Helen Ling's IBM 1620 computer room on the second floor in Building 202, which was centrally located in the middle of the Systems Analysis Section. The presence of all those boxes of UCLA-generated trajectory computations created quite a congestion. Thus began a highly unusual working relationship involving Minovitch, UCLA, and JPL that ran from June 1962 to September 1964 -- a type of relationship that probably never occurred before or since that time.

June 1962 Meeting with Clarke

In early June 1962, Stanley Ross and a group of nine other leading astrodynamicists from Lockheed (including J. Breakwell and R. Gillespie) completed an extensive analysis of interplanetary trajectories for manned space travel.[42] This work contained a numerical determination and analysis of non-stop and stop-over round-trip trajectories to Venus and Mars (Earth-Venus-Earth and Earth-Mars-Earth). It essentially confirmed the results of the previous studies.[31-33]

The Lockheed report also contained a determination and analysis of free-fall trajectories of vehicles launched normal to the ecliptic plane. These trajectories were considered important for exploring regions of the Solar System above and below the ecliptic plane (and for possible precursor manned interplanetary missions). The analysis concluded with a well known fact: reaching regions of the Solar System far from the ecliptic plane require enormous launch energy.[43,44]

The report ended with a graphical analysis of multiplanet non-stop trajectories. A detailed examination of this section of the report (Section 5) reveals how the leading trajectory researchers at that time viewed non-stop free-fall round-trip multiplanet trajectories, and why they were regarded as impractical without nuclear propulsion. Quoting directly from page 5-1 of this report:[42] "At the outset, we are confronted with a paradox: Low-energy transfers to Mars seldom dip appreciably within the Earth's orbit while, on the other hand, low-energy transfers to Venus rarely stray outside the Earth's orbit. These contradictions make it painfully apparent that the trips presently sought will not likely be found among low-energy transfer orbits. Nevertheless, the problem is worth considering not only as an interesting academic pastime, but also because the velocity requirements required in some cases may actually be attainable using presently envisioned nuclear power planets." Since this conclusion confirmed all previous numerical investigations of free-fall round-trip multiplanet trajectories,[35,45] it was concluded that such trajectories required very high launch energy and that this was also an unchangeable fact based upon the unchangeable dynamics of planetary orbits (also see pages 11, 12 of ref. 1).

It was taken for granted (as in all previous investigations of non-stop free-fall multiplanet trajectories) that these trajectories can be assumed to be essentially constant elliptical paths with the primary trajectory design consideration being placed on timing to meet the required planetary interceptions. Crocco's original analysis was based on this assumption and he demonstrated that as far as launch energy was concerned, this assumption was valid.[34] There was no expectation that anything would change. In particular, the Lockheed study appeared to demonstrate (with mathematical certainty) that using multiplanet trajectories would only result in <u>increasing</u> the propulsion requirements for traveling to another planet. With this theoretical framework, the possibility of using multiplanet trajectories for reducing the launch energies below the classical

Hohmann limit was a fundamental impossibility.

One of the earliest gravity-propelled trajectory profiles that Minovitch investigated on the UCLA 7090 computer was Earth-Venus-Mars-Earth. This was the type of profile that he gave to Gene Bollman for testing in April with JPL's high-precision numerical integration interplanetary trajectory program (which was used to verify that Minovitch had indeed numerically solved the Restricted Three-Body Problem). By June, at UCLA, Minovitch had determined the minimum launch energy corresponding to the 1970 launch window for this particular profile. The minimum launch hyperbolic excess velocity v_∞ was 3.26 km/sec, and the total trip time was 622 days.

Since his gravity-propelled trajectories had a C_3 launch energy (v_∞^2) less than one-tenth the required launch energy for Crocco's Earth-Mars-Venus-Earth constant elliptical path trajectory[34,35,42] and about half the trip time of low-launch-energy Earth-Mars-Earth trajectories that were numerically analyzed by Battin[31] and the group of ten astrodynamicists at Lockheed,[42] these gravity-propelled trajectories represented a distinctly new discovery in astrodynamics. It was believed that the combination of low launch energy non-stop round-trip trajectories to Mars and trip times in the range of 400 to 600 days was an astrodynamic impossibility. Thus, Minovitch's gravity-propelled trajectories meant that interplanetary space travel to Mars would be much easier than previously believed. The launch trajectories were within the launch capability of the NOVA class launch vehicles,[46] and nuclear propulsion was unnecessary. The concept of gravity-propelled trajectories, therefore, changed the entire situation for manned interplanetary space travel to Mars.

Minovitch disclosed these results to Clarke when he arrived at JPL in June 1962 to use the JPL computers. Minovitch recalls this meeting with Clarke:

> "In actuality, this meeting was really two meetings. The first meeting occurred one or two days before the second. In the first meeting, I think I just walked into his office and showed him the raw trajectory calculations that I made at UCLA, which had very low hyperbolic excess velocities and total trip times a little over 600 days. Clarke was familiar with Battin's analysis of Earth-Mars-Earth trajectories [31] which required trip times of over 1,000 days, so he realized that the trajectories I showed him were significant. The trajectories I gave to Bollman to check in April required more launch energy. But these trajectories had really low launch energies [lower than Battin's which were believed to be the absolute minimum launch energies for round-trip missions to Mars], and the distances of closest approach to Venus and Mars were well outside the atsmosphere. Clarke was very interested in these trajectories because the implications for manned round-trip interplanetary missions to both Venus and Mars were obvious. When I came to the second meeting at about eight o'clock in the evening, Clarke was with Jim Scott, the supervisor of JPL's programming group from the Computing Section. He and Scott were looking at that big Lockheed report [42]. I was happy to see that report because it essentially concluded that unless super-sized launch vehicles are developed, together with high specific impulse nuclear propulsion, manned missions to Mars would be impossible. It also concluded that non-stop multiplanet trajectories were impractical without nuclear propulsion because they required very high launch energies. That report clearly demonstrated the novelty of my concept of gravity propulsion where multiplanet trajectories are used to reduce the propulsion requirements of space travel. But Clarke was still skeptical in the beginning and suspected that my computer program might be generating erroneous planetary position vectors. He and Scott spent about half an hour checking my planetary position vectors corresponding to various Julian Dates against data known to be correct. They found no errors. I emphasized that the program was correct because it was checked by Bollman in April. But these trajectories were so different and made manned round-trip interplanetary space travel so easy that Clarke was almost unbelieving. I don't think he was aware (or comfortable) with the underlying gravity-propulsion analytic methodology that I used to calculate my multiplanet trajectories based upon Three-Body interactions. But after the meeting was over, I'm sure both he and Scott believed the trajectories were accurate. Clarke told me that Ross and Battin would be very surprised to see my trajectories. It was obvious that he was going to make my trajectories known to these people and to many others in NASA."

The method Clarke used to transmit Minovitch's low launch energy, short trip time, Earth-Venus-Mars-Earth trajectories to the Lockheed group was explained to Minovitch in 1986 by Raoul Roth (a trajectory programmer in Scott's programming group[1] who did most of Clarke's trajectory programming). Clarke not only transmitted some of Minovitch's UCLA computer calculations, he actually forwarded a duplicate copy of Minovitch's gravity-propelled multiplanet trajectory program that he used to calculate them.[47,48] At that time, there was no other trajectory computer program like that in existence, i.e., its design was contrary to the underlying analytical methodology and procedures used at that time for computing both one-way and round-trip interplanetary trajctories. At that time, all interplanetary one-way conic trajectory computer programs were based upon direct-transfer trajectories from a launch planet to a target planet -- which was regarded as so basic, it was never questioned. Minovitch's UCLA gravity-propelled trajectory program was based upon indirect transfer trajectories where the gravitational influence of an intermediate planet(s) supply a large part of the propulsion requirements. See, for example, refs. 1-19 of ref. 1. Thus, when Clarke forwarded Minovitch's program to Lockheed, he was forwarding a new idea for space travel.

Minovitch feels that this is exactly what he would have done if he were in Clarke's position at that time. The implications of Minovitch's propulsion concept and his ability to calculate previously incalculable trajectories based upon Three-Body gravitational interactions had enormous consequences for the U.S. interplanetary space program. But Clarke never directly informed Minovitch of his actions, nor was the application of Minovitch's gravity-propelled trajectory program ever acknowledged by the recipients at Lockheed. It should be noted, however, that no one in the Lockheed group claimed originality,[49] but the inconsistencies in the post- 1962 published accounts were very evident.[50,51]

Direct Access to the JPL 7090 Computers

When Minovitch came to JPL to use their computers at the beginning of the summer of 1962, arrangements were made with Carl Theis, who then headed JPL's computer operations, to run his programs on their two IBM 7090 computers on a time-available basis, which was usually late at night and during the weekends. Scheduling was done on large blackboards mounted in each of the two 7090 computer centers (in Buildings 125 and 202). Every time a large block of time was available, Minovitch would appear with his computer programs and special planetary ephemeris tape.

When Minovitch was working late at the UCLA computing facility, he often studied the IBM 7090 operating manual and, by watching the computer operator at that facility, he learned to operate the 7090 system himself. When he came to JPL, he demonstrated this ability to Carl Theis and the unusual interruptable operating features of his UCLA computer programs. Consequently, Theis gave instructions to the regular computer operators to simply turn the computer over to Minovitch when his time slot appeared and to go home. This did not make the operators very happy, but it reduced JPL's operating budget. Minovitch preferred this arrangement because the gravity-propelled trajectory program was difficult to start, and it usually had to be ended manually by dumping the core on a special save-tape. This was not a standard operating procedure and, if not done carefully, resulted in the loss of the core data on the save-tape. The program required four tapes to operate: two data output tapes, the special ephemeris tape, and a save-tape.

As in the UCLA 7090 system, each of the two JPL 7090 computers comprised about twenty-five large refrigerator-size tape drives, a central control console, a large on -line printer, an on-line card reader, and various subsystems such as high-speed printers, 1401 processing systems, and very large magnetic storage drums. The operating console was centrally located and resembled an upright piano with a large keyboard of about 60 operating keys. The console was equipped with about 200 small lights that flashed when various internal processing systems were being used during program execution. By studying the light patterns flashing on the control console, Minovitch was able to monitor the execution and determine if the program was operating properly.

When Minovitch arrived at JPL in June, his gravity-propelled trajectory program was still in an experimental state and prone to becoming trapped in an infinite loop. By monitoring the flashing lights, he was able to immediately determine when the program hung up in an infinite loop. In most cases, when this occurred, he would stop execution, change the value of an "ε-test" in the solution of an equation, and restart the program with very little down time. But some problems were more serious and required changes in the basic FORTRAN program. When these problems occurred at UCLA, the operator would have to terminate program execution and the computer would be restarted with someone else's program. Thus, Minovitch was grateful to JPL (particularly to Carl Theis) for letting him have direct access to both of the five-million-dollar IBM 7090 computers during most weeknights and weekends, and many afternoons and evenings. On many occasions, the computer runs at JPL would begin at about 10 PM and continue without interruption to 6 or 7 AM the following morning. On many occasions, Minovitch would arrange to transfer several boxes of computer paper from JPL to his office at WDPC while using both of the JPL computers. He would deliver the new paper to WDPC and take previously printed paper back to JPL. Before the beginning of each day shift, a crew of IBM 7090 system specialists gave each of the two JPL 7090 computers a series of tests to make sure these complex "super computers" were operating properly. Minovitch usually operated the computers through the entire night into the morning up to the arrival of the IBM systems engineers.

Minovitch often used both of the JPL 7090 computers simultaneously. He was also using the UCLA 7090 computer during this time. Consequently, with the combined computational power of three giant IBM 7090 digital computers, his research project rapidly grew to one of the most intense non-military computational research projects conducted at that time. Carl Theis and many of the computer operators in Buildings 125 and 202 had Minovitch's home phone number and his UCLA and JPL office phone numbers. If an unexpected block of time became available, Minovitch would be called, and he would use that block of time for his trajectory calculations (day or night). The use of the computers on a stand-by, time-available basis essentially kept all three computers operating around the clock, 24 hours a day, seven days a week.

The launch of Mariner I to Venus on Friday night July 22, 1962, was very exciting.[52,53] A loudspeaker had been set up in a large conference room at JPL to monitor communications between JPL and the launch control center at Cape Canaveral for the benefit of JPL employees wishing to follow the countdown. After about one hour had passed, a message was received indicating that the spacecraft had failed to achieve its pre-injection parking orbit. Minovitch was deeply disappointed. However, the failure rendered both of JPL's 7090s idle for the weekend. He took advantage of the situation by going on the machines less than one hour after the failure. This was the beginning of one of his longest uninterrupted computing periods. On one of the machines, it lasted over 37 hours.

The input data that the computer program used to compute gravity-propelled trajectories was: (1) the trajectory profile mission matrix NP(I,J) of integers defining the planetary encounter sequences $P_{0j} - P_{1j} - P_{2j} - \cdots - P_{nj}$ ($2 \leqq n \leqq 9$; $j = 1,2, \cdots, m \leqq 10$) for m different mission profiles; (2) a range of launch dates T_{0j} ; and (3) a range of first planetary encounter dates T_{1j}. The initial numerical investigation involved determining these trajectories for all possible $P_0 - P_1$ launch windows within the ten-year time span 1965-1974 where P_0 = launch planet (usually Earth). The investigation proceeded in three steps.

The first step involved determining whether or not the window contained any physically realizable gravity-propelled trajectories corresponding to a given trajectory profile under investigation. This involved sweeping through each $P_0 - P_1$ launch window with a "course grid" of various launch dates T_0 and initial transfer times $T_1 - T_0$. This grid $(T_0, T_1 - T_0)$ was formed by starting with certain initial values for T_0 and $T_1 - T_0$ at the beginning of the window, and then incrementing $T_1 - T_0$ by a certain time interval (usually six-day intervals) until a certain maximum value was reached. When this happened, T_0 was incremented to a new date and the process of incrementing $T_1 - T_0$ was repeated, beginning with the initial value. Only trajectories having positive distances of closest approach, which corresponded to physically realizable trajectories, were printed.

The second step in the numerical investigation involved making another sweep through the window using a finer grid size but only through that portion of the window that generated physically realizable trajectories. This second sweep usually had a 2-day x 1-day grid size.

The third sweep was essentially a repeat of the second sweep but with a much finer grid size. A 2.0-day x 0.2-day grid size was common for the third sweep, but sometimes the third sweep had a 1.0-day x 0.1-day grid size. Consequently, if a certain profile was possible for a certain window, many hundreds of this trajectory type were calculated for this window. This enabled the rate of change of distances of closest approach corresponding to changes in T_0 and $T_1 - T_0$ to be investigated for a sensitivity analysis. Sometimes the maximum distances of closest approach to the surface of a planet (e.g., Venus or Mars) were only 200 km. This is why the concept required a valid numerical solution to the Restricted Three-Body Problem. Errors of only 10% in the distances of closest approach to a planet's center could translate into errors of several hundred kilometers in the distances of closest approach to the planet's surface (making apparent physically realizable trajectories unrealizable in actuality). The vast number of trajectory calculations also made it possible to determine the minimum launch energy trajectory for each launch date in the various windows and the corresponding absolute minimum launch energy trajectory. Thus, it was possible to determine the most favorable trajectories. But the most important fact in the vast "catalogue" of trajectories being computed was the ability to choose any one in the catalogue and determine the corresponding actual trajectory (by the converging differential correction process) where the vehicle moved under the influence of all the bodies in the Solar System acting simultaneously. It was this fact that made the concept an engineering possibility.

The sheer volume of the trajectory calculations was difficult to manage. Since all the calculations were printed on three-ply paper, several boxes were needed to print the output tapes after each computer run. The printed output paper was fed into a special machine called a "burster" that separated the paper into individual sheets that were accumulated in three different piles. The use of three-ply paper often caused the machine to jam, which made the page separation process hectic and time-consuming.

The piles of individual pages were bound in book form and labeled, identifying the particular encounter sequence $P_0 - P_1 - P_2 - \cdots - P_n$, the first launch date, the last launch date, the time increment ΔT_0 between successive launch dates T_0, and the time increment ΔT_1 between successive arrival dates T_1 at the first planet P_1. The launch dates T_0 spanned a particular $P_0 - P_1$ launch window. All of the printed output from the UCLA 7090 computer was transported to JPL and also bound into individual books using the same bursting machines. These books were accumulated and stored along the wall in one of the large Section 312 conference rooms on the second floor of Building 202. The job of separating the printed output paper into individual sheets and binding them in book form was done by Minovitch, usually late at night while making long computer runs.

Minovitch's Uncompleted Theoretical Paper of August 1962

Although Minovitch was extremely busy with his computational investigation of gravity-propelled trajectories during the summer of 1962, he spent some time studying the theoretical aspects. Since he recognized that his research was on a level of a Ph.D. dissertation in mathematics or physics, he spent some time deriving Lambert's equations using the mathematical principles of Hamiltonian Mechanics. But he did not have the necessary time to devote to this and related theoretical research, and this paper was never completed.[54]

The Possible Gravity-Propelled Multiplanet Mission of 1962

The launch of Mariner II to Venus on August 27 was highly successful, and the JPL computers were used for telemetry analysis and orbit determination for about a week. After a few days of tracking following the launch, 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 date as input to his gravity-propelled program, Minovitch calculated various encounter trajectories required at Venus to achieve Earth-Venus-Mercury, Earth-Venus-Mars, and Earth-Venus-Earth trajectories. Minovitch found that an Earth-Venus-Mercury trajectory for Mariner II was not possible (it required a negative distance of closest approach with Venus' surface), but the two other trajectory profiles were possible. He gave this information to JPL's Mariner II trajectory group, and these possibilities were seriously considered.[55] Thus, the first multiplanet gravity-propelled interplanetary mission could have taken place eleven years before the 1973 Mariner 10 Earth-Venus-Mercury mission. However, the planetary approach guidance system onboard Mariner II was not sufficiently accurate to carry out these gravity-propelled trajectories with a sufficiently high probability of success, and the required $\vec{B}\cdot\vec{T}$ and $\vec{B}\cdot\vec{R}$ approach parameters were never transmitted to the Mariner II spacecraft.[56]

The JPL Extended High-Accuracy Planetary Ephemeris Development Project

When Minovitch came to JPL to use their 7090 computers during the summer of 1962, he was given an office in Building 202 (which he shared with another person). He was also on the Section 312 Distribution List for all Interoffice Memorandums and Technical Memorandums, etc. On one occasion, a paper was left on his desk describing a high-accuracy planetary ephemeris development project at JPL involving a certain numerical integration method. The project was being conducted in JPL's Computing Section. Since Minovitch needed an extended ephemeris to conduct his outer planet gravity-propelled trajectory investigation, he made some inquiries to ascertain when the project would be completed. He was told that the project would end sometime near the end of 1962 or possible early 1963. Thus, Minovitch became aware of the fact that JPL would soon have a very accurate planetary ephemeris that would extend at least 20 years beyond his ephemeris which ended in 1980. This is just what he needed to compute multiplanet gravity-propelled trajectories involving the outer planets.

Manned Landing Mission to Mars Without Nuclear Propulsion

As described above, the classical manned landing mission to Mars employing Hohmann minimum-energy transfer trajectories requires a total trip time of about 1,000 days. This long trip time was the result of having to wait 455 days on Mars (after arriving) for the minimum-energy Hohmann return Mars-Earth trajectory. This classical Hohmann mission profile is shown in Fig. 6. Since this mission profile requires such a long trip time, it was considered to be beyond human endurance. It was believed, without question, that the only possible way to reduce this total trip time was to use high energy departing and returning trajectories, examples of which are shown in Fig. 7 (also see ref. 30). Since the required launch energies were so high, the launch vehicle(s) had to be enormous (called Super-NΘVA or Sea Dragon) and required high-thrust nuclear-propelled upper stages.[1] Consequently, the high cost to develop the huge launch vehicles and high-thrust nuclear propulsion systems made a manned landing mission to Mars essentially impossible. However, by employing his concept of gravity propulsion, Minovitch designed a mission profile that did not require enormous launch vehicles and could be carried out without nuclear propulsion.

During the summer of 1962, Minovitch was able to calculate several thousand gravity-propelled trajectories of the form Earth-Venus-Mars and Earth-Venus-Mars-Earth. By combining these trajectory profiles, Minovitch designed a relatively short trip time manned landing mission to Mars with a total characteristic velocity ($\Sigma\Delta V_i$) much lower than the conventional short trip time, high-energy trajectories.[30] The design involved launching two different space vehicles using two launch vehicles. One, vehicle A, would be launched on a low energy nonstop Earth-Venus-Mars-Earth round-trip trajectory. This vehicle would be manned by a skeleton crew of one or two astronauts, but it would have room to accomodate a crew of five or six astronauts. It would be launched with an Apollo-type Earth re-entry module with a thickened heat shield. Since the required launch energy would be so low, this interplanetary space vehicle could be launched with a single NOVA-class vehicle[46] using conventional chemical rocket propulsion for all stages.

The second interplanetary vehicle, B, would be similar to A but would carry a small Mars landing module instead of an Earth re-entry module. Minovitch viewed the design of this landing module as similar to the Apollo lunar excursion module. The crew of B would consist of three or four astronauts with enough food for only about 300 days. When B approached Mars, the crew would enter the landing module, and the interplanetary vehicle would be abandoned without attempting to decelerate it by any retro propulsion. Thus, the total mass would be relatively low. Consequently, since the trajectory of vehicle B also would require relatively little launch energy, it would be easily within the launch capability of a single NOVA vehicle with all-chemical propulsion.

The trajectories of A and B were designed to allow the landing module of B to land on Mars a few days before A made its closest approach to Mars. The design strategy was such that the crew of B would land on Mars via the landing module, explore the surface of Mars for a few days (e.g., five or ten days), launch off the surface when A would begin its closest approach, and rendezvous with A. The crew of B would transfer into A, and the excursion module would be abandoned. The remaining voyage would be completed in A and both crews would return to Earth in the re-entry module.

Minovitch analyzed this mission profile for two different launch windows. The first window occurred in 1970 and required a total trip time of about 650 days. The second launch window occurred in 1972 and required a total trip time of only 500 days. Since a manned landing mission to Mars -- the principal target of space travel since Tsiolkovsky's writings -- was now a technical and economic possibility, Minovitch's ideas and research project became very important.

Gravity-Propelled Interplanetary Mass Transportation System

Another uniquely novel concept that Minovitch envisioned as a direct consequence of his gravity-propelled theory of interplanetary space travel was a gravity-propelled "interplanetary mass transportation system" that could last forever. In this concept, giant vehicles or space liners could be launched from Earth with very low hyperbolic excess velocity onto gravity-propelled trajectories having an unlimited number of planetary encounters $P_0 - P_1 - P_2 - P_3 - \cdots$. Such vehicles could then be used for shuttling passengers around the Solar System from planet to planet at very low cost. Passengers on one planet wishing to travel to another planet could simply "catch a ride" on a passing vehicle going to the desired planet via small transfer modules. When approaching the destination planet, the passengers could board the transfer modules, which would leave the interplanetary shuttle as it passed the destination planet, and then land on its surface, while the interplanetary shuttle vehicle was gravitationally propelled to the next planet without rocket propulsion in an unending series of planetary encounters. Since the propulsive forces acting on a gravity-propelled vehicle increase automatically with vehicle mass as prescribed by the Newtonian equivalence principle (see page 15, ref.1), the mass of the gravity-propelled shuttle vehicles is of no consequence. Thus, they could be huge rotating toroidal space liners capable of accomodating thousands of passengers in a comfortable earth-like artificial gravity environment more luxurious than the finest ocean liners. Since the shuttle vehicles (space liners) would not require any major onboard propulsion system and could be maintained enroute, they could be used indefinitely to transport an unlimited number of passengers around the Solar System at very low cost.

Minovitch numerically determined many gravity-propelled trajectories having up to eight successive planetary encounters with very low launch energy which would make repeated passes of Venus, Mars and Earth that could be continued indefinitely. However, the determination of these trajectories required a significant amount of computer time. For example, the determination of one realizable trajectory having a series of eight planetary encounters required about ten minutes of 7090 time. About 50 such trajectories were calculated to determine their characteristics. This concept of a never-ending gravity-propelled interplanetary mass transportation system moving continuously from planet to planet around the Solar System became known in the literature as the "cycling" concept.[57]

End of Summer 1962

When the fall semester started in September, Minovitch moved back to Dykstra Hall on the UCLA campus and resumed his formal graduate studies in mathematics and physics. As he did during the spring semester, he continued his gravity propulsion research project simultaneously with his formal academic studies. Although he had to divide his time between his research and his academic studies, the fact that the UCLA computer was close to his residence at Dykstra Hall made it relatively easy to continue the numerical investigation. His access to the JPL computers also continued throughout the entire project from June 1962 through September 1964. By October, he had reached the point where only relatively short periods of computing time were needed to complete the first phase of his research project (involving the inner Solar System).

December 1962 Meeting with Professor Michael Melkanoff at the UCLA Computing Facility

By the end of November 1962, Minovitch had completed all of the computer calculations he needed for his numerical investigation of gravity-propelled multiplanet trajectories involving the inner planets and started writing up the results in a lengthy technical report. (This report would not involve Jupiter or the outer Solar System as Minovitch intended to include this planet in the second phase of his research project where he expected to make use of JPL's extended ephemeris). In early December 1962, he learned that the new Chief of Computer Operations at WDPC was Dr. Michael Melkanoff. Melkanoff (who was one of Minovitch's undergraduate physics professors) wanted to review Minovitch's CF-09 research project at UCLA (with unlimited computing time) and the unusual relationship between JPL and UCLA. Melkanoff believed that since NASA and JPL would be the direct beneficiaries of Minovitch's UCLA research project, they should fund the project, or at least, part of the project, instead of the University of California. By that time Minovitch had already consumed over 150 hours of 7090 computer time at WDPC[58] and the demand for 7090 computing time was very high. (The number of universities and colleges using the UCLA 7090 at this time was almost 100.) Minovitch was concerned that since the computations for the first phase of the research project were completed, Melkanoff would feel no reason to continue the project (at significant cost to the University of California). In the meeting with Melkanoff, Minovitch explained the history of the project, and the fact that JPL recognized its UCLA origin and was only assisting Minovitch by contributing additional computing time. At that time, no one at JPL was working on the concept and no one there was assigned to assist Minovitch. But in December 1962, Minovitch knew that his rocketless propulsion concept would revolutionize space travel. He expressed this belief to Melkanoff and showed him some of the results of the computer calculations. He explained the limitations of chemical rocket propulsion and the fact that the mass ratio of a rocket-propelled vehicle increased exponentially with propulsive ΔV (given by the rocket equation) making high ΔV missions technically impossible with chemical rocket propulsion. At that time, it was commonly believed without question that this fundamental barrier to most of the Solar System could only be circumvented by developing high specific impulse nuclear propulsion and/or electric propulsion (ion propulsion), which was very expensive.[59-64] Moreover, the much-publicized development of nuclear and electric propulsion systems rested on assumed future technical advances that did not have a solid engineering basis. Thus, the root of the problem of exploring the Solar System was not funding, but rather basic engineering feasilibility. Minovitch explained that his concept of gravity propulsion, in contrast to nuclear and electric propulsion, rested on solving a mathematical problem -- the Restricted Three-Body Problem -- rather than on any engineering problem. Minovitch explained that he developed a practical numerical solution to this problem at JPL during the summer of 1961 which was verified at JPL in April 1962 by detailed numerical integration/iteration tests. This solution provided the basis for his concept of gravity propulsion and his huge numerical research project. The solution represented a new development in physics (analytical mechanics) which had unforeseen consequences in space travel which was being investigated by Minovitch. Melkanoff, a professor of physics, understood that the unsolved Restricted Three-Body Problem was one of the most famous problems in classical physics and that the first numerical solution was an important achievement. Minovitch explained that it represented the key to exploring the entire Solar System. At the end of the meeting, Melkanoff was convinced that Minovitch's UCLA research project was important and recommended continued UCLA support for the second phase with unlimited access to the 7090 computer.[65]

Since JPL did not begin its own gravity propulsion research project in 1962, Melkanoff may have felt that if UCLA terminated the project, Minovitch's use of the JPL computers on weekends would be discontinued. One could speculate that Melkanoff, being more familiar with the "facts of life" of research projects, may have seen a possible danger to Minovitch's research at JPL from powerful vested interest groups pushing electric propulsion.[59] Those groups would not be very happy to see how easy it would be to accomplish the "impossible" high ΔV interplanetary missions with a computer and a small planetary approach guidance system.

Completing the First Report

After completing the numerical calculations for the inner planet trajectory investigation in November 1962, it took Minovitch about three months to analyze the data and write up up the results in a lengthy 130-page report[66] that contained 36 figures and 24 numerical tables. The preparation of the report was done simultaneously with his academic studies, course assignments, and final examinations. The report contained a discussion of the concept, a theoretical section that described his solution to the Restricted Three-Body Problem, and a long discussion involving the results of the numerical investigation and various gravity-propelled trajectory profiles that he discovered as a result of this investigation. The theoretical section closely followed his original 1961 paper.[10]

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Planetary Configuration For Earth-Venus-Mars 1970
(August 12 Trajectory)

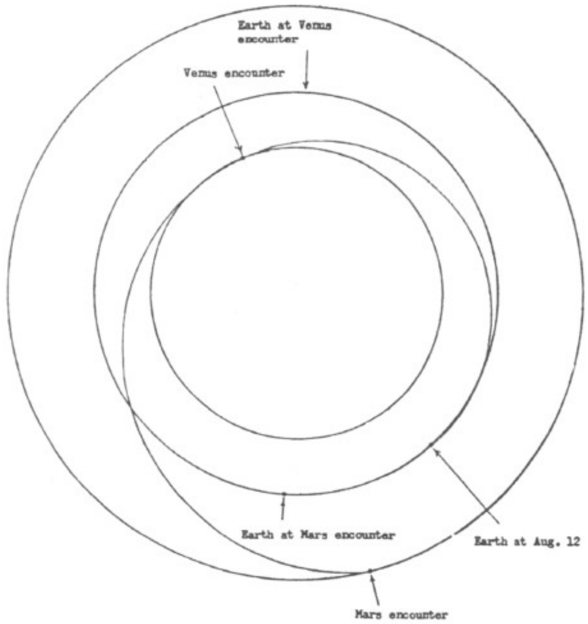

Figure 27

Fig. 8 Reproduction of Fig. 27 from Minovitch's March 4, 1963 JPL report illustrating how a vehicle can be sent to Mars with low launch energy outside the classical Earth-Mars launch window by using an Earth-Venus launch window and gravity-propulsion received from Venus.

The three most important gravity-propelled trajectory profiles that he numerically calculated and meticulously analyzed during this phase of his numerical investigation were: (1) Earth-Venus-Mars trajectories, which enable vehicles to be sent to Mars with very low launch energy and with launch dates far outside the classical direct-transfer Earth-Mars launch windows; (2) Earth-Venus-Mars-Earth non-stop round-trip reconnaissance trajectories with launch energies below "minimum launch energy" Earth-Mars-Earth round-trip trajectories[31] and having one-half the trip time of Earth-Mars-Earth trajectories and included passing Venus; and (3) Earth-Venus-Mercury trajectories, which enabled vehicles to be sent to Mercury with launch energies one-third to one-fourth that of the classical Hohmann "minimum-energy" direct-transfer Earth-Mercury trajectories.[38] Figs. 8, 9, and 10, which correspond to these trajectories, are reproductions of Figs. 27, 34, and 23, respectively, taken from this report.

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Planetary Configuration For Earth-Venus-Mars-Earth May 27, 1972

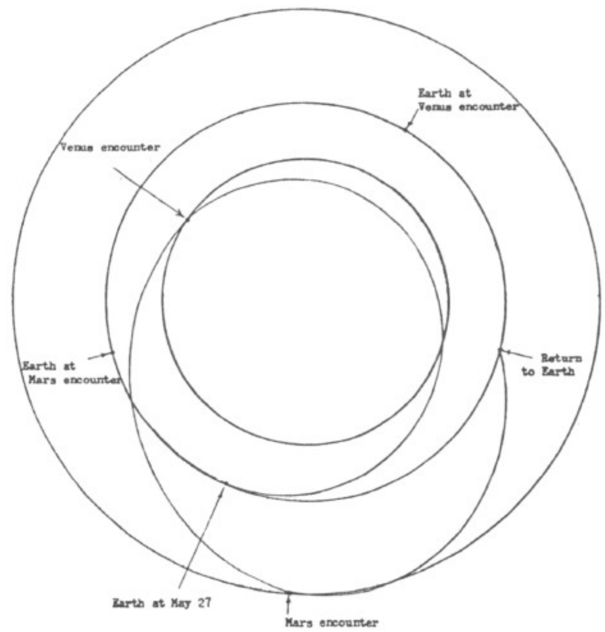

Figure 34

Fig. 9 Reproduction of Fig. 34 from Minovitch's March 4, 1963 JPL report illustrating how the concept of multiplanet gravity-propulsion can be utilized to obtain short trip time, low launch energy round-trip non-stop reconnaissance trajectories for manned interplanetary space travel.

The significance of these discoveries is profound in the history of interplanetary space travel because they (i.e., the concept of gravity propulsion) completely overturned the fundamental principles based upon direct-transfer "minimum-energy" Hohmann trajectories and reaction propulsion that were believed to be the unchangeable foundation of interplanetary space travel.

The numerical investigation also included the determination and analysis of single-planet round-trip trajectories to Venus and Mars of the form Earth-Venus-Earth and Earth-Mars-Earth. The results of this analysis were also included in the report which he used to demonstrate the advantages of his gravity-propelled, low launch energy Earth-Venus-Mars-Earth multiplanet round-trip trajectories. The paper also contained a discussion of gravity-propelled interplanetary transportation systems having an unlimited series of planetary encounters $P_0 - P_1 - P_2 - P_3 - \cdots$ that could be used for transporting an unlimited number of passengers around the Solar System.

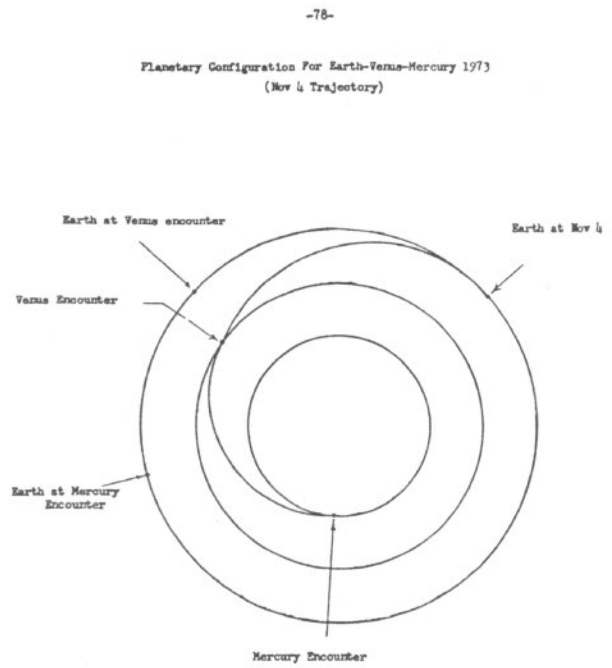

Fig. 10 Reproduction of Fig. 23 from Minovitch's March 4, 1963 JPL report illustrating how a vehicle can be sent to Mercury using relatively little launch energy needed to reach Venus, and gravity propulsion from Venus.

Instruction for the 1962-63 fall semester at UCLA ended January 12, 1963 and final examinations ended on January 23, 1963. The spring semester 1963 started January 28, 1963. Minovitch, as usual, started the spring semester by enrolling with another full load of graduate courses in mathematics and physics.[8]

JPL Technical Seminars February 4-5, 1963

There was a great deal of interest in Minovitch's research project at JPL (but at that time, it may have been primarily curiosity). He was invited to present this research in a series of two technical seminars. On Monday and Tuesday, February 4-5, 1963, Minovitch presented two one-hour technical seminars on gravity-propelled interplanetary space travel to the engineering staff of JPL's Systems Analysis Section (Section 312).[67]

The first seminar was primarily theoretical and directed at the overall concept of multiplanet gravity-propelled space travel and the mathematical techniques Minovitch developed for solving the system of N-Body Problems corresponding to a gravity-propelled trajectory generated by n planetary encounters $P_0 - P_1 - P_2 - \cdots - P_n$. The second seminar was devoted to presenting specific examples of gravity-propelled trajectories discovered by the numerical investigation involving the inner planets and how they could be used for reducting the propulsion requirements for both manned and unmanned interplanetary space travel through the inner Solar System. Minovitch recalls the first seminar:

"Almost all the Section 312 Senior Staff Personnel were present for the first seminar. They included C.R. Gates, Tom Hamilton, William Melbourne, Jack Lorell, Harry Lass, Carl Salloway, and Vic Clarke. Many other engineers also attended. Sam Dallas, Gene Bollman, and William Kirhofer were also present. I suppose about 30 or 40 came to the first seminar. I began by presenting the general concept of gravity-propelled interplanetary space travel as I had done on pages 38 - 44 of my 1961 paper [10]. But I didn't refer to the concept as "gravity propulsion" or "gravity-propelled space travel." I think I just called it "advanced space travel." I presented some of my vector analysis and used this analysis to prove that the orbital energy of a free-fall vehicle can be changed relative to the Sun by the gravitational influence of a passing planet. [Although this fact was known to most astronomers, it was not common knowledge among engineers in the early 1960s.[1,68]] I described how it is possible to utilize this effect as a propulsion concept to catapult a vehicle all around the Solar System with major trajectory changes relative to the Sun without using any reaction propulsion by gravitationally bouncing from one planet to another planet and illustrated the concept by giving various encounter sequences Earth - $P_1 - P_2 - \cdots - P_n$. I did not restrict this discussion to the inner planets and pointed out that because of their great mass, the larger outer planets would provide the most dramatic trajectory changes. I also pointed out the fact that the concept required a numerical solution to the "unsolved" Restricted Three-Body Problem and proceeded to show how I was able to solve this problem by decoupling it into a series of Two-Body Problems and employing a purely vector representation for conic orbits instead of the usual six orbital element representation. Carl Pfeiffer [who at that time was a recognized authoirty on guidance and celestial mechanics] objected to my "turning off" the Sun's gravitational influence when the vehicle passes close to a planet. I described more details about Tisserand's moving "sphere of influence" that I used in the patched conic solution that was evidently not very well known at JPL at that time. I mentioned the fact that Bollman tested my solution in April 1962 using JPL's high precision trajectory integration program and that my analytical methods actually represented a numerical solution to a system of N-Body Problems. In retrospect, I don't think that very many engineers at that meeting were very excited about my ideas or recognized the possibilities because only about ten people came to the second seminar. Maybe they just wanted to see who that strange person was who was consuming so much 7090 computer time and wasn't even a regular JPL employee. I didn't feel that they recognized the mathematical celestial ballet concept of interplanetary space travel I envisioned that didn't require a rocket engine. Perhaps this was because they were engineers and wanted to explore the Solar System with brute force rocket power. But I had a lot of respect for those engineers because they laid the foundation for our space program. The only way that my propulsion concept could be used was via a rocket-propelled escape maneuver from Earth which those engineers were developing."

During the second seminar, Minovitch described how the Earth-Venus-Mars, and Earth-Venus-Mars-Earth gravity-propelled trajectory profiles could be used to carry out a manned landing mission to Mars with low launch energy for both the outbound and return legs (as in the classical profile) but without requiring a 455-day waiting period on Mars before the launch back to Earth -- a feat previously believed to be impossible. Moreover, since the total propulsion requirements were low, no nuclear propulsion systems would be required, and the required launch vehicles could be much smaller than the giant "Sea Dragon" or "Super Nova" vehicles previously believed to be required.[69,70] As a result, the overall cost of a manned landing mission to Mars could be significantly reduced. Since the most expensive part in the standard plan for the manned Mars mission appeared to be the development of super launch vehicles and nuclear rocket propulsion, the application of Minovitch's ideas would have probably reduced the mission cost to one-fourth the expected cost. Minovitch believed that a cost reduction of this magnitude would make the mission possible. If a manned landing mission were not undertaken, he believed that his low launch energy short trip-time Earth-Venus-Mars-Earth trajectories could be used to at least carry out a manned nonstop reconnaissance mission of both Venus and Mars.

Although Minovitch considered possible manned missions to Mars the most important immediate application of gravity-propelled trajectories, manned missions were outside JPL's space exploration directive assigned by NASA. But Minovitch's research was not being directed by JPL or NASA. His research followed a course that he believed would result in the greatest possible benefit to the United States -- a manned mission to Mars in the 1970-75 time period made possible by substituting inexpensive gravity propulsion for very expensive nuclear propulsion. He believed that JPL could help him make this possibility known to NASA so that it could be taken into consideration when a final decision was reached. However, Minovitch knew that his concept of gravity-propelled space travel would affect all interplanetary missions (manned and unmanned) and that is why he constructed his computer program to include encounter sequences involving all of the planets in any order with up to nine planetary encounters in any sequence.

The last gravity-propelled trajectory profile that Minovitch discussed in the second JPL seminar was Earth-Venus-Mercury (see Fig. 10). Many hundreds of trajectories of this type were computed, as Minovitch believed that this type would be the first application of the concept. It enabled an unmanned reconnaissance vehicle to reach Mercury with the very low launch energy required to reach Venus -- a reduction of about one-third to one-fourth of the previously believed minimum C_3 launch energy corresponding to the classical Earth-Mercury Hohmann trajectories. This reduction meant that the mission could be carried out by a relatively small launch vehicle such as the Atlas, instead of the very expensive Saturn previously believed to be required. Minovitch's extensive computer analysis found that the best Earth-Venus launch windows for this profile occurred in 1965, 1970, and 1973. The 1973 window was eventually used. The mission became known as Mariner 10.[71]

Minovitch concluded the seminar with a discussion of his concept of gravity-propelled interplanetary mass transportation systems.

Election to Life Membership in the National Physics Honor Society Sigma Pi Sigma

When Professor J. Robert Oppenheimer was teaching theoretical physics at the University of California, Berkeley, during the 1930s, he started a weekly Tuesday evening meeting of advanced graduate students and faculty members from the physics department. It became known as the "Journal Club" and was used as an informal meeting for physics professors to present their most recent papers. A similar "Journal Club" was started by UCLA's Physics Department, and Minovitch usually attended these meetings. Because of these weekly meetings and the numerous graduate physics courses he was taking at that time (1960-1964), physics professors assumed that Minovitch was a regular graduate student in physics. But he was formally enrolled as a graduate student in mathematics.

During one of his many nights at WDPC, Minovitch met one of his previous physics professors, Dr. Harold Ticho. Professor Ticho was using the UCLA 7090 computer to analyze data from a high-energy nuclear physics experiment performed on one of the accelerators at the University of California Berkeley's Lawrence Laboratory. Since Minovitch attended the weekly Journal Club meetings so often, Ticho assumed that he was doing work on his Ph.D. dissertation in physics and asked him about it. Minovitch described his research project and the fact that it was based on his numerical solution to the famous Restricted Three-Body Problem. Ticho believed that this problem was either unsolvable or very difficult because of Poincaré's work and was very impressed with Minovitch's accomplishment. Minovitch described how the University of California was supporting the research with an unlimited amount of 7090 computer time, and that JPL was also making available both of their 7090s. The fact that Minovitch formulated a new concept for interplanetary space travel based on his solution to this difficult problem and that he was using three IBM 7090 computers to numerically investigate the concept on his own initiative was very unusual for a "student." The conversation didn't last more than 15 minutes and Minovitch quickly forgot about it.

A few weeks later, after one of the Tuesday night Journal Club meetings, Minovitch was asked to attend a Sigma Pi Sigma meeting that was just starting in another room of the physics building. At that time, Minovitch didn't know what the Sigma Pi Sigma Society was, but he was told someone was going to give a talk on physics. Minovitch entered the room and sat near the back. After the lecture was over, a physics professor stood up and gave a short one-minute speech about the election of a special graduate student to life membership in the UCLA Chapter of the National Physics Honor Society of Physics Students, Sigma Pi Sigma. The person nominated for life memberhip was Michael Minovitch. Cake and ice cream were passed around and Minovitch received some congratulations. He was never told how he was elected to this honor society, but it was evidently a result of his research project and his meeting with Professor Ticho.

First Graduate Academy of the University of California

Minovitch's concept of gravity-propelled interplanetary space travel and his large-scale numerical investigation were also becoming known and discussed in UCLA's Department of Mathematics and in the School of Engineering. On several occasions, a mathematics professor would ask Minovitch how his research project was going and for some details about his numerical solution to the Restricted Three-Body Problem.

On March 21, 1963, Minovitch received an invitation from the Chancellor of UCLA, Dr. Franklin D. Murphy, to present his research in an annual academic meeting of all the University of California campuses called the Graduate Academy, to be held during the spring recess April 6-9, 1963.[72] This was a prestigious academic conference wherein each University of California campus selects advanced graduate students from various fields engaged in exceptional Ph.D. research. Minovitch was selected to represent UCLA in the Physical Sciences.[73] The program also included Classical Music and Ballet performed in UCLA's large Royce Hall auditorium. It was a beautiful festival and celebration of scholarship, creativity, and the advancement of knowledge. Since space travel was a new and fascinating subject in those days, there was a lot of interest in Minovitch's talk. Minovitch recalls this occasion:

> "I gave my presentation in a large auditorium in the Chemistry Building on April 8. Since almost every seat was taken, there must have been about 600 in the audience. There was a large blackboard that I used to draw the orbits of all the planets in the Solar System to the approximate proper scale. I explained the classical method of space travel via direct-transfer P_0 - P_1 Hohmann trajectories using brute force rocket power and my concept of gravity-propelled space travel $P_0 - P_1 - P_2 - \cdots - P_n$. I recall illustrating the concept on the blackboard with a long encounter sequence that ended in a string of outer planets. It may have had the form Earth-Venus-Mercury-Venus-Earth-Mars-Jupiter-Saturn-Uranus-Neptune. At that time I was thinking about finding a trajectory that encountered all of the planets in the Solar System except Pluto. [Minovitch knew from his planetary configuration diagrams that since Neptune would be leading Pluto for many years, a sequence having a segment Neptune-Pluto would be physically unrealizable.] I explained that this concept required a numerical solution to the unsolved Restricted Three-Body Problem and briefly described my solution and how it was verified at JPL. I ended by explaining how I used this solution to construct a large FORTRAN computer program to numerically investigate this concept of space travel on the UCLA 7090 computer and the two 7090 computers at JPL. After the session was over, while I was walking out the door, a few individuals met me, wanting to know more details about the concept and my research project. We talked for about a half an hour. Many different planetary encounter sequences were mentioned involving the inner planets and the outer planets. The program ended with a beautiful ballet performed in Royce Hall by students with the musical score from Mussorgsky's 'Pictures at an Exhibition.' It was very moving, and I will never forget that academic festival."

Minovitch's paper was published in the Proceedings of the first Graduate Academy of the University of California.[74]

First AIAA Western Region Student Conference

In early 1963, the American Rocket Society (ARS) merged with the Institute of Aerospace Sciences (IAS) to become the American Institute of Aeronautics and Astronautics (AIAA). Its first president was Dr. William Pickering, who was also director of the Jet Propulsion Laboratory.[75] The student branch of the IAS became the student branch of the AIAA. An annual AIAA student conference was organized in six geographical regions of the United States where participants presented their own technical papers based on their original research. There were three basic divisions: Undergraduate, Masters, and Ph.D. The papers in each division were judged competitively and three awards were given. The winning Ph.D.-class paper of each region then competed for the national award.

Since the AIAA Western Region Student Conference was a natural forum for Minovitch to present his research, he was encouraged by UCLA's School of Engineering to submit a paper. Minovitch accepted this invitation and prepared a short paper. As in the case of his UCLA paper,[74] this paper was basically a shortened version of his March 4, 1963 JPL report.[66] On April 19, he was notified that the paper was accepted as a Ph.D. category paper[76] and it was formally entered into the conference.[77] The conference, held May 2-3 in the large Pan Pacific Auditorium in Los Angeles, was attended by many aerospace engineers and academicians. Minovitch recalls this conference:

> "I gave this talk on Friday morning May 3, 1963. The Pan Pacific Auditorium was a very large place. I was extremely nervous about speaking in front of such a large audience. However, I knew that my concept of gravity propulsion would have a major impact on future interplanetary space travel, and I was eager to explain it to a large group of professional aerospace engineers. There was a big model of the first Wright Brothers 1903 Flyer hanging from the ceiling and I became

very emotional. I felt the Wright Brothers were sitting in that audience. I looked up at that model and said that I was going to present a new method for space travel that would extend man's exploration of the Solar System beyond what is currently believed to be possible. I said it in a way that was sincere so I don't think it was interpreted as a casual boast but rather, as a deep conviction. I described various encounter sequences and explained how a vehicle can be gravitationally catapulted from planet to planet with major trajectory changes relative to the Sun without using any rocket propulsion. I also described how the concept could be used to carry out a manned landing mission to Mars with non-nuclear NOVA launch vehicles. My presentation was about 30 minutes long and received a warm applause. After I gave the talk, several engineers from some local aerospace companies asked me for more details about the concept. We talked for about half an hour. It was clear to most of the engineers that Jupiter would provide the most dramatic trajectory changes and would be the primary propulsion planet for opening up the entire Solar System to exploration with relatively small chemical launch vehicles. Electric and nuclear propulsion were no longer necessary to accomplish these missions. At the end of the conference, it was announced that my paper won First Place [78-81] and I received the $100 winning check with a handshake from Dr. William Pickering. The paper was published [82] one year later."

This conference is significant in the early history of gravity-propelled interplanetary space travel because it was the first time that Minovitch described the concept to a large group of professional aerospace engineers. They came from several NASA centers and from various aerospace companies.[77] The conference also included a large industrial aerospace products display. It was a large gathering and, in view of the great size of the famous Los Angeles Pan Pacific Auditorium, the number of engineergs who heard Minovitch's talk must have exceeded 1,000.

Jupiter and Exploring the Entire Solar System

Minovitch's computer-based numerical investigation of gravity-propelled multiplanet trajectories through the inner Solar System essentially ended around November 1962. But, since he did not want to lose any opportunity to use the UCLA computer, he usually gave the third shift 7090 operator long runs to do with his stand-by save-tape. This was how he began the detailed numerical investigation of gravity-propelled trajectories involving Jupiter and the outer planets (the second phase of his research project). Melkanoff cleared the way by continuing to give Minovitch access to the 7090 computer without time limitations.[65] By this time (December 1962) the project was becoming one of the most intense computational investigations at WDPC.

Since Minovitch was aware of the fact that the gravitational influence of Jupiter was far greater than any other planet and therefore had the potential for generating the most radical post-encounter trajectories, he realized that this planet could gravitationally catapult a free-fall vehicle to essentially any target body in the Solar System. Unfortunately, he was still unable to obtain an extended planetary ephemeris from JPL to conduct extensive multiplanet gravity-propelled trajectory calculations involving the outer planets. However, since direct-transfer trajectories to Jupiter require relatively high launch energies, he began investigating the possibility of lowering the Jupiter direct-transfer launch energies by gravity propulsion generated by encountering one or more intermediate planets with trajectories of the form Earth $- P_1 - P_2 - \cdots - P_{n-1} -$ Jupiter where $P_i =$ Venus, Earth or Mars. These trajectories did not require an extended ephemeris and have the potential for propelling a free-fall vehicle to Jupiter with a launch hyperbolic excess velocity V_∞ approximately equal to the minimum required for reaching the first planet P_1. Thus, if $P_1 =$ Venus, $V_\infty \approx 3$ km/sec. The launch hyperbolic excess velocity required for direct-transfer Earth-Jupiter trajectories is about 9 km/sec. Thus, by employing gravity-propelled trajectories generated by the inner planets, the previously assumed minimum launch energy required to reach Jupiter ($V_\infty^2 \approx 9^2$ km^2/sec^2) could be reduced by a factor of $9^2/3^2 = 9$ -- and, after reaching Jupiter, the vehicle could then be gravitationally catapulted to any other target in the Solar System.

The implications of this possibility are significant because it means that traveling to any planet in the Solar System, exploring regions far above or below the ecliptic plane, impacting the Sun, or escaping from the Solar System altogether and exploring interstellar space can be achieved with only the minimum amount of launch energy required to reach Venus.

```
THIS IS RECONNAISSANCE MISSION NUMBER   5
HELIOCENTRIC EQUATORIAL COORDINATE SYSTEM EPOCH 1950.0
LAUNCH PLANET = EARTH
VENUS
ARRIVAL PLANET = JUPITER
INJECTION ALTITUDE = 200.00 KM

SAVE  CALLED AT THIS POINT***
      LINES OUTPUT THIS JOB.
END OF OUTPUT FOR  CF098******
```

Fig. 11 Reproduction of a computer output listing illustrating Minovitch's search for low launch energy gravity-propelled trajectories to Jupiter generated by encountering the inner planets. Listing made January 1963, Research Project CF-09 UCLA Computing Facility.

Fig. 11 is a reproduction of one of Minovitch's CF-09 computer runs[83] made during this time (January 1963) in a search for low launch energy trajectories to Jupiter via Earth-Venus-Jupiter profiles. The absence of any numerical data under the profile type indicates that no realizable trajectories were found for this profile. The investigation usually proceeded by analyzing up to ten different profile types in a single computer run. The profiles most often analyzed were Earth-Venus-Earth-Jupiter; Earth-Venus-Earth-Mars-Jupiter; Earth-Venus-Mars-Earth-Jupiter; Earth-Venus-Earth-Earth-Jupiter; and Earth-Venus-Earth-Earth-Mars-Jupiter corresponding to many different Earth-Venus launch windows.

It is interesting to note that Minovitch's idea of conducting multiplanet gravity-propelled space travel through the outer Solar System with low launch energy generated by gravity propulsion using the inner planets was not new to Minovitch in December 1962. He recognized this possibility in August 1961 and illustrated the principle with a trajectory of the form Earth-Venus-Mars-Earth-Saturn-Pluto-Jupiter-Earth in his August 23, 1961 paper (page 39, ref. 10).

The disadvantage of using gravity propulsion to reach Jupiter was that it made the trip time to Jupiter longer. But the advantage was that these trajectories had the potential for reaching Jupiter with very low launch energies. Such trajectories also made it possible to conduct close scientific observations of each intermediate planet on the way to Jupiter. Minovitch did not regard this investigation as very successful because he was searching for, but did not find, trajectories with very low launch energy ($V_\infty \approx$ 3 km/sec). This investigation also required substantial computer time because of their sensitivity in the launch parameters. Small changes in T_0 and T_1 resulted in significant changes in the distances of closest approach. (However, a similar investigation conducted by Minovitch in the spring of 1967 at the University of California Berkeley using a more powerful CDC 6400 computer was more successful.[84])

This technique of reaching Jupiter with gravity propulsion generated by encountering the inner planets is currently being used in the Galileo mission to Jupiter via an Earth-Venus-Earth-Earth-Jupiter trajectory profile.[85]

When Minovitch originally constructed his multiplanet gravity-propelled trajectory program at UCLA under Project MA-11 during February and March 1962, he used Lamber's equations corresponding to elliptical interplanetary legs to determine their semi-major axes.[14] He did this to make the analysis (and the computer program) as simple as possible so that he could concentrate on the most important question he had at that time: did his analytical methods actually represent a numerical solution to the unsolved Restricted Three-Body Problem. However, he was aware of the fact that a close planetary encounter with a large planet such as Jupiter could transform an elliptical pre-encounter trajectory into a hyperbolic post-encounter trajectory. Minovitch pointed out this fact in his August 23, 1961 JPL paper (page 19, ref. 10) and indicated how such trajectories could be calculated in the proposed computer program described in that paper.[10] He explicitly gave the detailed functional form of Lambert's hyperbolic trajectory equations in a July 11, 1961 paper,[86] which included an analytic and graphic analysis. This paper[86] also included an analytical method for determining the semi-major axis of any conic path passing between two given points corresponding to a given trip time that could be either elliptical or hyperbolic (the trajectory type didn't matter).

Since Minovitch initially concentrated his investigation of gravity-propelled trajectories on the inner planets (with manned missions to Mars being the most important application), there was no immediate necessity to modify the program in order to calculate hyperbolic post-encounter trajectories. At that time (summer 1962), when giant multi-billion dollar battleship-size launch vehicles with nuclear upper stages were being seriously proposed for manned missions to Mars,[36,69] his primary aim was focused on demonstrating how his concept of gravity-propelled space travel could be used to make the manned Mars missions possible without nuclear propulsion and with much smaller launch vehicles. This was by far the most important area for immediate investigation. However, after Minovitch finished this investigation[66] (and other possible missions involving the inner Solar System), the program modification was made and many trajectories of the form Earth-Jupiter-Saturn and Earth-Jupiter-Uranus (with hyperbolic post-encounter Jupiter-Saturn and Jupiter-Uranus legs) were computed. The Earth-Jupiter-Saturn trajectory profile was eventually used in NASA's Pioneer 11 and Voyager 1 missions launched in 1973 and in 1977, respectively.[87-89] But a systematic investigation of these trajectories (and many others with multiplanetary encounters) corresponding to the most favorable launch windows in the 1970s still required an extended planetary ephemeris that Minovitch believed he would soon obtain from JPL. Therefore, this particular area of the numerical investigation had to be postponed until the extended ephemeris was obtained.

During early 1963, Minovitch constructed an entirely new gravity-propelled trajectory program. This program was designed to determine the precise trajectories that a free-fall vehicle should have while approaching a perturbing planet (such as Venus) that would maximize the vehicle's post-encounter trajectory's distance from the Sun and distance out of the ecliptic plane. This program was completed in March 1963. The analytic method involved solving a long equation that was very sensitive to the variable parameters. This method proved to be numerically unstable, and he abandoned the program. Since his full load of graduate studies (attendance, course assignments and examinations) were taking place simultaneously with his gravity propulsion research, the demand on his time was acute.

1963 Denver AAS Symposium on the Exploration of Mars and the Saturn V Possibility

At the beginning of June 1963, the spring semester at UCLA ended, and Minovitch continued his UCLA gravity propulsion research project using the JPL computers as he had the previous summer. Tom Hamilton, (who at that time was a senior manager in JPL's Systems Analysis Section 312), was aware of Minovitch's keen interest in the manned exploration of Mars and arranged for him to attend a large AAS symposium in Denver, Colorado, June 6-7 on the exploration of Mars. Minovitch made the trip with two regular JPL employees, Jack Lorell and Sam Dallas, and brought along some extra copies of his March 4, 1963 paper.[66]

One of the papers presented at the symposium described a small Mars landing vehicle[90] that used atmospheric braking for a major portion of the decelerating landing maneuver instead of retro-rocket propulsion that Minovitch used. After making some rough slide-rule calculations, Minovitch found that by using this landing vehicle, the manned Mars landing mission profile he designed using gravity-propelled interplanetary transfer trajectories could be accomplished with three Saturn V launch vehicles instead of two NOVA launch vehicles. By employing atmospheric braking at Mars instead of braking by retro-rocket propulsion, the resulting mass savings was so large that the vehicle carrying the landing module on the Earth-Venus-Mars trajectory could be launched using two Saturn V vehicles instead of one NOVA vehicle. One Saturn V would be used to launch the vehicle with some propellant into a low Earth orbit, and a second Saturn V, acting as a tanker, would fill the vehicle with the required remaining propellant. The vehicle carrying the Earth re-entry module launched on the Earth-Venus-Mars-Earth non-stop trajectory would be launched by a third Saturn V vehicle. Consequently, a manned landing mission to Mars could be achieved essentially with the same basic launch vehicle capability being developed for Project Apollo. The development of new NOVA class launch vehicles would be unnecessary.[46] Compared to the development of the Saturn V vehicles, the development of a small Mars landing vehicle using atmospheric braking[90] would be relatively easy. It was therefore apparent that a manned landing mission to Mars could be incorporated into the basic Apollo Program with nearly the same funding levels. Minovitch viewed the situation with excitement and deep concern. Since he knew that the launch ΔVs required for his gravity-propelled trajectories were correct, he viewed the AAS paper[90] as providing the basic engineering feasibility for carrying out the Mars landing mission with three Saturn V launch vehicles and conventional chemical rocket propulsion.

One of the featured speakers at that Symposium was Dr. Harry Ruppe. Ruppe (who was one of the original Peenemünde engineers working with von Braun) presented a paper[91] describing his ideas and design proposals for a manned landing mission. His general approach was based upon using classical direct-transfer trajectories with very high launch energies in order to reduce the total trip time.[30] As was usually the case, the launch energies required for the departing and returning legs were so high that nuclear propulsion systems were required, together with huge "Sea Dragon" class launch vehicles. (The total initial mass in Earth orbit was 1,200 tons.[91]) Minovitch decided that he had to tell Ruppe his ideas about gravity propulsion and, in particular, how these ideas could be used to carry out a manned landing mission to Mars without nuclear propulsion and without battleship-size launch vehicles.

After Ruppe finished his talk, Minovitch introduced himself and explained that he was also working on manned missions to Mars but using a new concept in trajectory design involving indirect gravity-propelled multiplanet trajectories to reduce the launch energy requirements. Minovitch gave him a copy of his JPL March 4 paper[66] and later mailed him a revised copy incorporating atmospheric braking and a detailed quantitative analysis demonstrating the Saturn V possibility for a manned landing mission.[92]

A few weeks later Minovitch received Ruppe's reply.[93] Ruppe did not see any particular advantage in using gravity propulsion for missions to Mars and evidently associated the concept with Crocco's high energy multiplanet trajectories. (See pages 11, 12 of ref. 1.) In his reply,[93] he mailed Minovitch another paper he wrote on the exploration of Mars[94] based upon classical direct-transfer trajectory designs and the huge launch vehicles and nuclear propulsion systems that resulted from these designs. There was no reference to the non-nuclear Saturn V possibility. At that time, Ruppe was working in NASA's Future Projects Office at the Marshall Space Flight Center. Nevertheless, Minovitch had great admiration for Ruppe. His lecture in Denver rang with inspiration and the hope that the United States would develop the huge launch vehicles and nuclear propulsion systems that he envisioned. But Minovitch believed that the cost to develop those giant launch vehicles and nuclear propulsion systems would render them unrealizable, and this would result in the cancellation of the Mars landing mission (and the cancellation of a possible non-stop manned reconnaissance mission).

There was another person at that Denver 1963 Symposium whom Minovitch also approached. His name was Maxwell Hunter II. He was a member of President Kennedy's National Aeronautics and Space Council. After Hunter gave his presentation, Minovitch introduced himself, briefly described his concept of gravity propulsion and, in particular, how it could be used to carry out a manned landing mission to Mars without nuclear propulsion. He also gave Hunter a copy of his March 4 JPL paper.[66] He later sent Hunter a revised copy of his paper that included the use of atmospheric braking and the resulting Saturn V possibility, hoping that he would recognize this important possibility and direct NASA's attention to it.[95]

July 1963 Meeting with Dr. Melkanoff

In July, Minovitch had another meeting with Dr. Melkanoff. During the months of May and June, Minovitch did not use the UCLA computer and wanted to advise Melkanoff that he planned on resuming the numerical investigation involving the outer planets. Melkanoff was still apprehensive that JPL was not supporting Minovitch's research project on the UCLA computer but was in a position to gain from the results of his research. But Minovitch emphasized the fact that JPL was still regarding the research project as a very theoretical University of California research project and therefore had no control over it. Minovitch's use of the JPL computers was a contribution to this UCLA project. In 1963, JPL still had no regular employees working in this field. The possible unmanned missions (such as Earth-Venus-Mercury and Earth-Venus-Mars that Minovitch finished analyzing) were still not regarded as serious possibilities, and gravity-propelled missions to the outer planets was rarely discussed. As far as JPL and NASA were concerned, these high-energy missions would be conducted separately to each individual planet by electric propulsion.[40,59-61] However, JPL (Section 312) did demonstrate great interest in Minovitch's project because they gave him access to essentially all their facilities (both secretarial services that he used for writing his papers and the computing facilities). This made him work even harder. Melkanoff recorded the meeting with another note for the UCLA Computing Facility.[96]

The Extended JPL Planetary Ephemeris and the Meeting with Dr. William Melbourne

Although Minovitch was given virtually

unlimited access to the JPL computers from June 1962 through September 1964, he discovered that he could not use the JPL computer programs, nor could he execute any "Request for Programming" to the Computing Section, for the assistance of a computer programmer. Since his UCLA research project was neither a JPL nor a NASA project, he was never given a "job number." All of the hundreds of hours he was using on the JPL computers (on a "time available," stand-by basis) were never charged to any JPL or NASA research project. This allowed him to use the JPL computers for his own UCLA gravity propulsion research project without connecting it to any JPL or NASA research project. This unusual arrangement was worked out in June 1962 to the mutual benefit of both Minovitch and JPL. But some disadvantages to this arrangement had negative consequences for Minovitch that he did not recognize in 1963 or 1964. This involved the JPL high-aecuracy extended planetary ephemeris. Minovitch recalls this time:

> "In August 1963, I called JPL's Computing Section regarding the status of the high accuracy extended planetary ephemeris project. After learning that the project was completed,[97] I went down to the computing section and asked one of the programmers who worked on the project to describe the ephemeris. The ephemeris was in the form of three magnetic tapes spanning the time period 1950-2000. The information was stored on the tapes with a specialized access computer code with which I was unfamiliar. I explained that I wanted a program to be constructed that would punch out the planetary coordinates of all nine planets on data cards corresponding to Julian Dates from 1960 through 2000 with certain time intervals depending on the particular planet in a certain format. He said that this would not be difficult but I would need a "job number" or a "Request for Programming" from William Melbourne. Since I didn't have a "job number," I went to see Melbourne about getting the "Request for Programming." When I met Melbourne I explained that I wanted to use the new JPL ephemeris to extend my ephemeris which ended in 1980. His response was completely unexpected. He explained that this could not be done because my research project was not a JPL or NASA project and had no project number for accounting purposes. I explained that the programming and computing time would only be a few minutes, but Melbourne would not do it. I asked him if I could simply charge the work to one of his job numbers or someone else's but he described this possibility as a serious violation. I accepted his explanation as ground rules that couldn't be broken -- part of the government bureaucracy of contract work. But this reason seemed that it could be overcome. I thought that he would give me a "job number" that I could use for my work with the JPL ephemeris in a day or two, but this never happened."

Minovitch considered the possibility of constructing his own extended ephemeris by calculating approximate planetary position vectors. By assuming that the osculating planetary orbital vectors ($\vec{e}$, $\vec{h}$) near 1980 were constant vectors for each planet, it was possible to calculate the approximate position vectors of the planets at any future time. However, Minovitch decided against this possibility because he believed that he would eventually gain access to the JPL ephemeris, if not in 1963, then in 1964. The prospect of using many hours of computing time at UCLA and JPL to calculate hundreds of inaccurate multiplanet trajectories to the outer planets with an ephemeris known to be inaccurate and then, after the calculations are finished, being presented with the high-accuracy JPL ephemeris, was unsettling.

In retrospect, it is interesting to note that in February 1962, when Minovitch was beginning his UCLA research project, Hollander advised Minovitch to forget about keypunching the British 1960-1980 planetary ephemeris book[13] (which he considered to be too difficult) and to construct an ephemeris by a numerical integration process using a method similar to that used in the construction of the British ephemeris. After the numerical integration program is constructed, it would be a simple matter to integrate the position vectors of all the planets in the Solar System way beyond 1980 and to automatically punch them out onto data cards in any format desired. However, Minovitch believed that this would consume more time than keypunching the British ephemeris and he decided against the idea. There was also the danger that a slight error would ruin the ephemeris and invalidate all the trajectory calculations made with it.

High-Accuracy Planetary Approach Guidance

During 1962 and the first half of 1963, when Minovitch began speaking about his concept of gravity-propelled interplanetary space travel, one of the most frequently asked questions involved the required planetary approach guidance. Unless a very accurate system could be developed, the concept would not be technically feasible. Since a vehicle's post-encounter trajectory $P_i - P_{i+1}$ ($i = 1, 2, \cdots, n-1$) is extremely sensitive to errors in the encounter trajectory around planet P_i, the approach trajectory to P_i has to be extremely accurate. Errors of only a few kilometers in position and a few meters per second in velocity when approaching P_i will result in missing the next planet P_{i+1} in the encounter sequence by hundreds of thousands or even millions of kilometers.

In 1962, the guidance systems used for unmanned free-fall interplanetary reconnaissance vehicles were not very accurate and were used for carrying out "mid-course" trajectory corrections to enable a vehicle launched on a direct-transfer trajectory to pass anywhere in the general vicinity of a target planet. But for multiplanet gravity-propelled trajectories, the required guidance system had to be many orders of magnitude more accurate. Minovitch spent part of the summer of 1963 developing analytical methods for determining required trajectory corrections for a gravity-propelled vehicle's planetary approach guidance system.[98] He used these methods to demonstrate the technical feasibility of his propulsion concept in terms of the required planetary approach guidance system, and to develop an optimum strategy for carrying out corrective guidance ΔV propulsive maneuvers to estimate and minimize the required propellant.

The Unmanned High Energy Missions

When Minovitch learned that the JPL extended planetary ephemeris may not be available in his research project, he did not consider this to be a major setback at that time. He felt that eventually this ephemeris would be made available. Moreover, the application of gravity propulsion to reduce the launch energies of the most difficult missions did not require an extended ephemeris.

The traditional direct-transfer high-energy missions for unmanned instrumented space probes were, in order of difficulty[59,60]: (1) missions out of the ecliptic plane with high inclination; (2) missions close to the Sun(impact); and (3) high-speed missions to the outer planets. The most significant application of gravity-propulsion in the first two missions would involve utilizing Jupiter to generate 90°-inclination post-encounter trajectories, and Solar-impact trajectories having the profiles Earth-Jupiter-90°-inclination, and Earth-Jupiter-Sun, respectively. The first hint that Jupiter would, in fact, be capable of generating radically different post-encounter trajectories came as the result of some initial slide-rule investigations made during the summer of 1961. Additional signs appeared in early 1962 involving the numerical computation of trajectories of the form Earth-Jupiter-Venus and Earth-Jupiter-Mercury. It was found that for these profiles, every low-energy Earth-Jupiter pre-encounter trajectory generated a realizable post-encounter leg with very large distances of closest approach. This indicated that by lowering the distances of closest approach, the post-encounter trajectory could be made to impact the Sun -- and this post-encounter trajectory would be a straight line with eccentricity equal to unity. At that time, it was believed that the only way a vehicle could be made to impact the Sun was to launch it in a direction opposite to the Earth's orbital motion with a velocity sufficient to cancel the Earth's orbital velocity such that it falls into the Sun along a straight line.[23,29] But this requires a launch hyperbolic excess velocity V_∞ = 30 km/sec and is way beyond chemical rocket propulsion.

The possibility of generating realizable solar-impact Jupiter post-encounter trajectories meant that by changing the Jupiter $\vec{B}\cdot\vec{T}$ and $\vec{B}\cdot\vec{R}$ approach parameters, it would be possible to generate post-encounter trajectories with 90° inclinations. These trajectories are even more difficult to obtain by the traditional direct method because it requires giving the vehicle a velocity component V_p that is perpendicular to the ecliptic plane. Thus, the required direct launch hyperbolic excess velocity $V_\infty = [30^2 + V_p^2]^{1/2} > 30$ km/sec.

Since Minovitch's multiplanet gravity-propelled trajectory program could not be used to calculate precise approach trajectories to Jupiter that would result in solar impact and 90°-inclination post-encounter trajectories, new computer programs would have to be constructed to numerically determine these trajectories. The analytical determination was based on Minovitch's vector methods and was completed before the end of the summer of 1963. (Some of this analytical work was done in 1961.)

Although the third high-energy mission did require an extended ephemeris, Minovitch believed that, for the time being, an alternative gravity-propelled trajectory profile could be investigated that would demonstrate Jupiter's propulsive ability to accelerate vehicles to the outer planets without requiring any extended ephemeris. This profile involved determining the required approach trajectory to Jupiter corresponding to a given pre-encounter trajectory such that the hyperbolic post-encounter trajectory has maximum energy relative to the Sun. Consequently, by calculating such gravity-propelled trajectories for all Earth-Jupiter launch windows contained during a complete revolution of Jupiter around the Sun (a 12-year period starting with launch dates from 1967 through 1978), Minovitch could investigate how the high-energy hyperbolic post-encounter trajectory sweeps 360° around the Solar System, passing the orbits of each of the remaining outer planets, Saturn, Uranus, Neptune and Pluto. By proceeding with the numerical investigation along these lines, it was only necessary to have Jupiter encounter dates within the time interval of the original planetary ephemeris -- a condition that was easily satisfied since the Jupiter intercept dates for gravity-propelled trajectories involving the outer planets fall within this time period. As in the previous two cases, a new computer program had to be designed and constructed to numerically determine these trajectories.

Minovitch's Method of Reporting His Gravity Propulsion Research

Although most of the engineers in Section 312 were not aware of the significance of Minovitch's concept of gravity-propelled space travel in 1963, a few were. Jack Lorell was one of those few. On one occasion when Minovitch was working on a small IBM 1620 computer in Building 202 during the summer of 1963, Lorell advised Minovitch that he should report his research in the form of many short technical papers that would cover a few weeks of research, rather than in long papers (such as his March 4, 1963 paper[66] that covered over a year of work). But Minovitch was not a professional. He did not like writing papers. His enjoyment was doing research, not writing about it. He planned to present the results of his theoretical work with Jupiter with the results of his numerical investigation.

It should also be noted that Minovitch was keenly aware of the many different trajectory profiles that could be used for specific missions. Although his aim was to numerically investigate the most important profiles to demonstrate the technical feasibility of his concept of gravity-propelled trajectories and how this propulsion concept could be used to make interplanetary space travel much easier than previously believed, he did not intend to cover the entire range of profiles. Being a theorist and not an engineer, he felt no particular need to do all the numerical trajectory computations. Any engineer or trajectory programmer, given a copy of Minovitch's multiplanet gravity-propulsion trajectory program and some diagrams of planetary orbits, could numerically calculate these trajectories. It was the underlying concept for which Minovitch wanted credit, not the individual missions. The concept was already documented in his August 23, 1961 paper.[10]

End of Summer 1963

The typical graduate student in a Ph.D. program in mathematics or physics usually completes the basic graduate subjects during the first two years, sets aside one or two semesters preparing for the rigorous Ph.D. examinations (and the foreign language examinations), finds a research project with the help of a faculty advisor, and completes the research with a dissertation. But Minovitch began his graduate studies in 1958 with a determination to study as much advanced mathematics and physics as possible.

After completing the basic Ph.D. courses in mathematics and physics, he continued into the advanced courses and seminars (with full course loads each semester) without pausing to take the examinations. After he started his gravity propulsion research in 1961, he had very little time left to prepare for the examinations since he continued to take a full load of advanced mathematics and physics courses. (Advanced courses and seminars in mathematics and physics were not offered routinely every semester.) However, at the beginning of the fall semester 1963, Minovitch did decide to set aside some time to prepare for the examinations that he planned to take during the spring of 1964. This time was found by taking two courses during the spring semester 1964 instead of enrolling in four courses as he usually did in every semester.[8] His gravity propulsion research continued, although at a somewhat reduced pace.

Interest in Gravity Propulsion by the National Space Council

Since Minovitch did not received any response from his meeting with Hunter during the Denver AAS Symposium, or from his June 26 follow-up letter[95] during the summer of 1963, he assumed that Hunter was not very interested in his concept of gravity propulsion and, in particular, how it could be used to accomplish a manned mission to Mars without nuclear propulsion using Saturn V launch vehicles. However, toward the end of October, he received a letter from Hunter that indicated he was very interested in the concept.[99] The letter contained a paper he wrote for the Executive Secretary of the National Aeronautics and Space Council who, at that time, was Dr. Edward Welsh. Since part of the paper[100] was based upon using gravity propulsion for unmanned exploration of the Solar System, Hunter asked Minovitch to review it prior to publication.[99] This resulted in more communication[101-106] which Minovitch hoped would lead to an invitation to join the Council to work temporarily on the concept under Hunter, but this never happened.

Continuing Interest in Minovitch's Gravity Propulsion Research at UCLA and JPL

By the beginning of December 1963, Minovitch had worked on the theoretical and numerical investigation of gravity-propelled space travel at UCLA for nearly two years. Over 200 hours of IBM 7090 computing time were used at UCLA, which made the project one of the largest university numerical investigations conducted at that time. Moreover, since Minovitch preferred to operate the computers himself (which allowed him to make changes and/or modifications in his programs within minutes), he probably used over 300 hours on the JPL computers by the beginning of December 1963. His March 4 1963 paper[66] was eventually published as a JPL Technical Report[107] that was also given to the UCLA Computing Facility. This highly unusual research project, funded by the University of California with a vast amount of computer time donated by JPL, caught the attention of many faculty members and visiting scholars at UCLA, and the Computing Facility asked Minovitch to provide a brief background description of his research project.[108] Particular interest centered on the fact that this project was the result of the first numerical solution of the Restricted Three-Body Problem.

Elliott Cutting, who (at that time) led JPL's trajectory group, also read Minovitch's 1963 Technical Report[107] and in January, encouraged him to rewrite it in condensed form as a paper for the AIAA Journal. Minovitch prepared a shorthand version for publication which Cutting reviewed.[109] Unfortunately, Minovitch could not find the time to make the revision suggested by Cutting, and the Journal paper was never published.

Summer of 1964

In April 1964, Minovitch took his Ph.D. examinations but the results were not satisfactory. (It cost him several weeks of study and interfered with his gravity propulsion research.) This created a feeling of frustration for Minovitch since he was doing independent research beyond the normal Ph.D. dissertation level, but he could not find the time to pass the basic Ph.D. qualifying examinations. However, by this time, he had completed the new FORTRAN gravity-propelled trajectory computer program at UCLA corresponding to the analytical solutions he developed the previous year for accomplishing the high-energy missions using Jupiter and Venus as the primary perturbing planets.[110,111] When the semester ended, he continued the numerical investigation at JPL and UCLA as he had done the previous two summers.

By the beginning of summer 1964, the IBM 7090 computers at WDPC and JPL were replaced by more powerful IBM 7094 computers. These computers were about three times faster than the 7090s.

As was usually the case, the new programs required considerable "debugging" and testing before they became operational. Each of these programs employed the direct-transfer trajectory program[18] as a subroutine to calculate the initial transfer trajectory from Earth to the sphere of influence of the perturbing planet. The new portion of the programs calculated the detailed approach trajectories inside the sphere of influence that would generate the desired post-encounter trajectories. The calculation of the post-encounter trajectories was also important because they represented "extremum" trajectories (i.e., the limiting trajectories that could be generated by the perturbing planet).

Minovitch's investigations during the summer of 1964 involved extensive computer analysis because a total of six different gravity-propelled trajectory programs were employed. The three Jupiter programs calculated Earth-Jupiter-solar impact trajectories; Earth-Jupiter-90°-inclination trajectories; and Earth-Jupiter-Deep Space trajectories (having maximum heliocentric energy). The three Venus programs calculated Earth-Venus-near Sun trajectories (having minimum heliocentric energy); Earth-Venus-out of ecliptic trajectories (having maximum distance from the ecliptic plane); and Earth-Venus-maximum distance from Sun trajectories, corresponding to various distances of closest approach.

The numerical investigation of the three types of Jupiter-propelled trajectories involved sweeping three times through each of the 11 Earth-Jupiter launch windows contained within the 12-year time span 1967-1978 corresponding to each trajectory type. Several hundred trajectories of each type were calculated for each window. The numerical investigation of the three types of Venus-propelled trajectories proceeded in a similar manner. Gravity-propelled extremum post-encounter trajectories generated by passing Mars were also investigated. The computer calculations at UCLA and JPL were essentially completed by the end of July 1964. (The faster operating speed of the IBM 7094 computers enabled the numerical investigation to proceed much more rapidly.)

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Technical Memo 312-514
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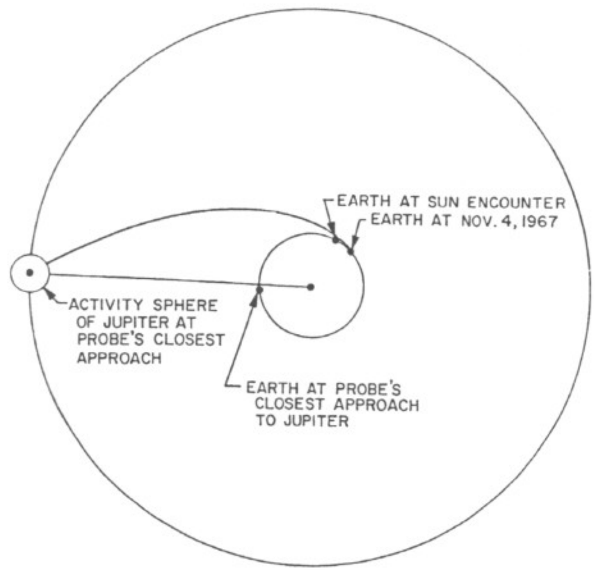

Fig. 30. Planetary configuration for Earth-Jupiter-Sun, 1967 (Nov. 4 trajectory)

Fig. 12 Reproduction of Fig. 30 from Minovitch's second JPL report[112] illustrating how a vehicle can be sent to the Sun using gravity propulsion from Jupiter. This profile requires a launch energy less than one-tenth of the previously assumed minimum-energy required for solar impact via classical direct-transfer trajectories.

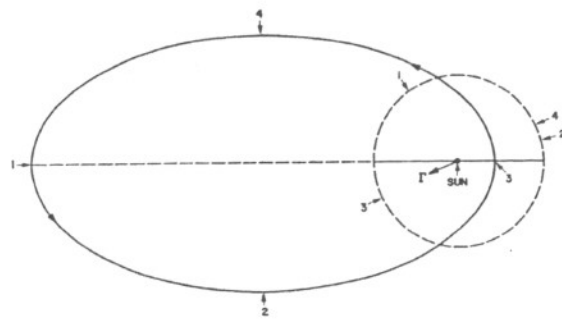

Fig. 59. Earth-Jupiter out-of-ecliptic, April 14, 1973 trajectory

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Fig. 13 Reproduction of Fig. 59 from Minovitch's second JPL report[112] illustrating how a vehicle can be sent out of the ecliptic plane on a 90°-inclination trajectory using gravity propulsion from Jupiter. This profile requires a launch energy less than one-twentieth of the previously assumed minimum energy required for classical 90°-inclination trajectories.

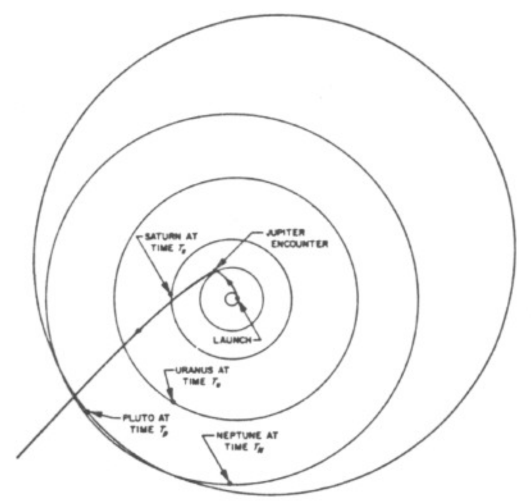

Fig. 14 Reproduction of Fig. 23 from Minovitch's second JPL report[112] illustrating how a vehicle can be sent on a high-speed deep-space trajectory past the orbits of Saturn, Uranus, Neptune, and Pluto using gravity propulsion from Jupiter.

Minovitch reported the results of this research, which essentially covered the time period December 1962 - July 1964, in another long paper[112] that was more like a book than a technical paper. It was 134 pages long and, in addition to numerous analytical sections, contained 49 numerical tables and 64 sepsrate figures. Figs. 12, 13 and 14 are reproductions of figures 30, 59 and 23, respectively, given in the report, illustrating examples of gravity-propelled Earth-Jupiter-Sun trajectories; Earth-Jupiter-90° out of ecliptic trajectories; and Earth-Jupiter-Deep Space trajectories. It was eventually published as a JPL Technical Report. The Earth-Jupiter-90°-inclination gravity-propelled trajectory profile (used for exploring the Solar System at great distances above and below the ecliptic plane and the North and South poles of the Sun) was eventually used in the Ulysses mission launched in 1990.[113] The Earth-Jupiter-Deep Space gravity-propelled trajectory profile was used in the Pioneer 10 mission.[114]

The Meeting with William Sjogren and the Gravity-Propelled Earth-Jupiter-Saturn-Uranus-Neptune Voyager 2 Trajectory Profile

Since the orbital period of Jupiter is about 12 years, the calculation of Earth-Jupiter-Deep Space trajectories corresponding to each of the 11 Earth-Jupiter launch windows contained in the 1967-1978 time period made it easy to identify outer planet encounter sequences and their launch windows for multiplanet gravity-propelled trajectories. In August, Minovitch selected a representative example of an Earth-Jupiter-Deep Space trajectory from each of the 11 launch windows in the 1967-1978 time span and plotted these trajectories superimposed on all of the planetary orbits of the outer planets. He also plotted the positions of all the outer planets in their respective orbits at the time when the hyperbolic Jupiter post-encounter trajectory passes the orbits of these planets. The result was a collection of 11 separate figures showing how the Jupiter-generated hyperbolic high-energy deep-space trajectories rotated 360° around the Solar system during the 12-year period passing the orbits of each of the remaining outer planets, Saturn, Uranus, Neptune, Pluto. This enabled easy identification of the particular launch windows (dates) corresponding to Earth-Jupiter-Saturn; Earth-Jupiter-Uranus; Earth-Jupiter-Neptune; and Earth-Jupiter-Pluto gravity-propelled trajectories. These figures were illustrated in Figs. 5, 7, 9, 11, 13, 15, 17, 19, 21, 23, and 25 in Minovitch's report. These figures also made it easy to identify possible gravity-propelled encounter sequences having more than two encounters. The particular encounter sequence Earth-Jupiter-Saturn-Uranus-Neptune corresponding to the 1977 Earth-Jupiter launch window was particularly evident.

Fig. 14, a reproduction of Fig. 23 of Minovitch's report,[112] illustrates an Earth-Jupiter-Deep Space trajectory crossing the orbits of the outer planets corresponding to a September 8, 1977 launch date. The positions of Saturn, Uranus, and Neptune indicate the possibility of an Earth-Jupiter-Saturn-Uranus-Neptune gravity-propelled multiplanet trajectory that was discussed between Minovitch and William Sjogren (an engineer in Section 312) at JPL during the summer of 1964. Minovitch recalls this discussion, which he documented in a letter to Professor Norris Hetherington (from the Department of History, University of Kansas) in 1974.[115]

> "One afternoon during the summer of 1964 (August or September), I was working at my desk in Bay 504 in Building 180 at JPL drawing figures illustrating the positions of all of the outer planets when the Jupiter generated hyperbolic deep space trajectories passed their respective orbits corresponding to various Earth-Jupiter launch windows. William Sjogren stopped by to say hello and to see what I was doing. I had these figures spread out all over the room. He saw the trajectories corresponding to the 1977 and 1978 launch windows, and noticed the corresponding positions of the outer planets. He pointed out the possible gravity-propelled trajectory profile Earth-Jupiter-Saturn-Uranus-Neptune. Since I was aware of this particular encounter sequence since February 1962, [see Figs. 2 and 3] which he had just noticed as obvious two and one-half years later, I looked at Sjogren with some frustration and said that 'if you can get the extended JPL planetary ephemeris for me, I will calculate the detailed trajectory parameters for these trajectories!' We walked out to the elevator corridor together and talked about this and other multiplanet gravity-propelled trajectory profiles involving the outer planets. This particular trajectory profile was eventually used in the Voyager 2 mission."

End of Summer 1964

During the summer of 1964, JPL took the first step toward implementing Minovitch's concept of gravity-propelled interplanetary space travel in an actual NASA mission. On June 11, Elliott Cutting issued the first formal Request for Programming to begin studying a possible gravity-propelled mission to Mercury via a trajectory profile of the form Earth-Venus-Mercury.[116] Cutting recognized the significant potential of Minovitch's ideas about gravity-propelled space travel and became an early advocate.[109,117]

Minovitch's ideas about gravity-propelled space travel also caught the attention of Conway Snyder from JPL's Space Science Division. Snyder organized a formal JPL conference on Flight Mechanics and invited Minovitch to give a talk describing how gravity propulsion could be used for accomplishing the high-energy missions[118] without electric propulsion. Minovitch accepted the invitation and prepared a talk entitled "Use of Planetary Gravity Fields for High-Energy Missions."[118] Unfortunately, Minovitch missed the conference which began at 10 AM. (Always a man of deeply entrenched nocturnal habits, Minovitch still routinely works from late afternoon to dawn -- he rarely awakes before 2 PM.)

Transfer to the University of California, Berkeley

Minovitch found great personal enjoyment during the three years that he spent investigating his concept of gravity-propelled interplanetary space travel and bringing it to the attention of professional astrodynamicists and important individuals connected with the U.S. Space Program. He believed that his extensive numerical investigation firmly established its technical feasibility and that the numerical investigation would be carried forward, if not by himself, then certainly by others. However, by the end of summer 1964, JPL still had no official NASA research project to conduct gravity-propelled multiplanet trajectory research. Minovitch was the only person connected to JPL who was doing this research at that time, but this was basically in support of his UCLA project.

Elliott Cutting believed that Minovitch would continue the research (as a JPL research project) and asked him to return to JPL during the summer of 1965. But Minovitch was not certain that he would be able to continue it in 1965. He was beginning to feel the effects of overwork. His original goal was to establish the theoretical and technical feasibility of his concept of gravity-propelled interplanetary space travel, and he believed that he accomplished this goal. His long-range career goals were in pure mathematics and theoretical physics. Although he enjoyed the research and regarded it as both basic research in mathematical physics (analytical mechanics) and space travel, he was also getting older and wanted to re-focus his energy on learning more advanced mathematics and physics and last, but not least, passing the Ph.D. qualifying examinations.

In September 1964, Minovitch decided to transfer from UCLA to UC Berkeley and complete his Ph.D. work there. The field of mathematics which he loved most was differential geometry. Dr. Shoshichi Kobayashi, a professor of mathematics at UC Berkeley, was one of the leading mathematicians developing the modern topological foundations of differential geometry,[119] and Minovitch wanted to study this field at Berkeley under Kobayashi. Moreover, Berkeley was also one of the world's leading institutions in theoretical and high-energy nuclear physics. One of Minovitch's most admired physicists who once taught at Berkeley was J. Robert Oppenheimer. To Minovitch, who still had his youth and ideas about other research projects in mathematics and physics, these things were important.

When Minovitch moved to Berkeley in September 1964, he was not finished with his report[112] and had to finish it in Berkeley. After it was finished he mailed it to Cutting and seriously considered returning to JPL to continue gravity propulsion research. With Cutting showing so much interest, he knew that there would be no problem obtaining the JPL extended ephemeris to numerically compute the outer planet gravity-propelled multiplanet trajectory profiles. But Minovitch was very tired during the spring of 1965 and needed to slow down. He had worked during the previous six consecutive summer vacations 1959-1964. Consequently, he decided to take the summer of 1965 off and spend it at Harvard University in an individual study program preparing (without any distractions) for his Ph.D. examinations at Berkeley. He planned to return to JPL during the summer of 1966 and advised Cutting of these plans.

Cutting was disappointed. In a letter dated May 21, 1965,[120] he told Minovitch that his report on the high-energy missions generated considerable interest in a possible gravity-propelled deep space mission to the outer Solar System and that he was planning to start preliminary studies for such a mission that summer. Minovitch was very happy. This was one of the reasons why he conducted his two-and-a-half year numerical investigation. Cutting and many others at JPL were finally convinced that Minovitch's concept of gravity-propelled multiplanet space travel was not only useful for exploring Mercury[116] but for exploring the outer planets as well.[118,120] This meant that the underlying propulsion principles for achieving interplanetary space travel would, except for a few cases, be changed (for the foreseeable future) from direct-transfer using reaction propulsion to indirect-transfer using gravity-propulsion. But it meant much more than a shift in propulsion methods, because very little of the Solar System could be explored with reaction propulsion since nuclear and electric propulsion were not technically viable in 1964 (and are still not technically viable in 1991). Therefore, it meant the opening up of the entire Solar System to direct exploration with instrumented space vehicles.

Historical Comments

This section is intended to address some of the questions that have been most often asked about Minovitch's gravity propulsion research and related topics. We shall also identify and explain some of the most common misconceptions.

JPL's Technical Capability of Computing Gravity-Propelled Multiplanet Trajectories after Minovitch Left in 1964

When Minovitch decided to spend the summer of 1965 at Harvard University, he did not leave JPL without any means for computing gravity-propelled multiplanet trajectories and continuing this research. He was aware of the fact that Clarke had reproduced his UCLA gravity-propelled multiplanet trajectory program[21] in June 1962[47] and, by 1964, that this program was in JPL's inventory of trajectory programs.[121,122] Although this June 1962 version of Minovitch's gravity-propelled multiplanet trajectory program did not have the modification necessary to compute hyperbolic post-encounter legs, the modification was not difficult. (The analytical details were explained in Minovitch's two 1961 papers.[10,86]) Likewise, the modification required to make the program operate with JPL's extended planetary ephemeris was not difficult. The program itself was very easy to operate. All that was necessary to operate it was to input a string of digits N_0, N_1, N_2, $\cdots$, N_n corresponding to any desired planetary encounter sequence P_0 - P_1 - P_2 - $\cdots$ - P_n (such as 3, 5, 6, 7, 8 for a Voyager 2-type trajectory) and a range of launch dates and trip times for the first leg.[21] Figs. 5, 7, 9, 11, 13, 15, 17, 19, 21, 23 and 25 of ref. 112 made it obvious what the likely outer planet encounter sequences would be for the various Earth-Jupiter launch windows. A single computer run with this program also had the capability of determining gravity-propelled trajectory profiles with up to nine planetary encounters, and up to ten different profiles could be calculated in each computer run. These techniques, together with an extended ephemeris, was used by Gary Flandro (whom Cutting assigned to run the calculations) during the summer of 1965 to numerically determine multiplanet gravity-propelled trajectories to the outer planets -- one of which was eventually realized in the Voyager 2 mission.[123]

There is another interesting aspect related to Minovitch's leaving JPL in 1964 that has never been told. Before moving to Berkeley in September 1964, Minovitch arranged to store essentially all of his computer calculations in a large storage basement in JPL's Building 180. This material included everything he kept at JPL, everything he had stored in his office at UCLA, and almost everything he had stored at his home in Los Angeles. Since almost everything that was printed was in triplicate, the pile was very large and consisted of about 200 bound books of output paper and over a dozen boxes of unbound printed output paper and computer programs. At that time, this collection essentially represented an enormous library of gravity-propelled interplanetary trajectories (and direct-transfer trajectories) covering many different launch windows and encounter sequences. It was the combined output of Minovitch's two-and-a-half year numerical investigation at UCLA and JPL. There was nothing like this collection anywhere in the world. In 1966, Minovitch discovered that it was all destroyed without any prior notification sent to either UCLA or to Minovitch.

Misconceptions Concerning the Frequency of Voyager 2 Trajectory Profiles

Numerous articles and books have been published that describe the planetary configuration required for a realizable Voyager 2-type Earth-Jupiter-Saturn-Uranus-Neptune gravity-propelled trajectory as a "rare event" that occurs only once every 176 years.[124,125] This is not true. Although the exact relative positions of Earth, Jupiter, Saturn, Uranus and Neptune that existed at the time Voyager 2 was launched (August 1977) will not reappear again for approximately 176 years, it will not require this many years before Voyager 2 gravity-propelled trajectory profile is possible.

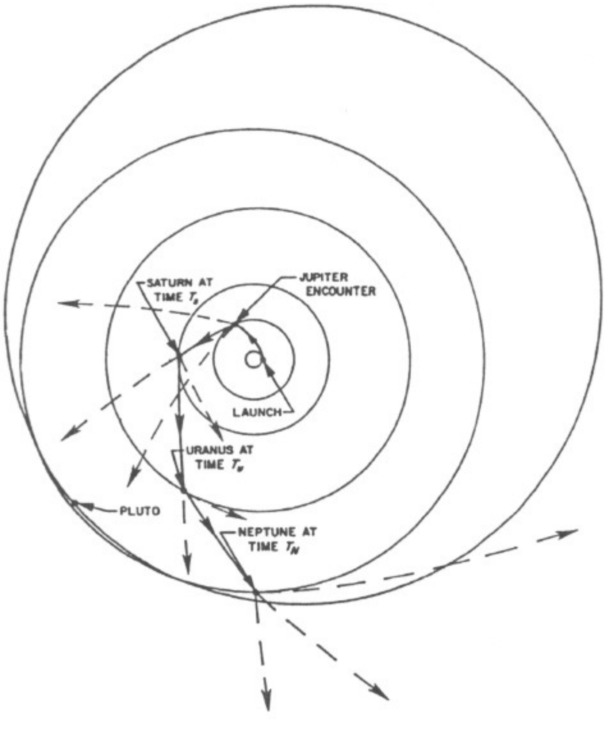

Fig. 15 Illustration of Voyager 2's gravity-propelled trajectory (solid line) and a few of the infinite course changes (dash lines) that can be realized at each planet by changing the approach parameters.

All of the outer planets in this particular encounter sequence have sufficiently large masses to catapult a free-fall vehicle to virtually any positive (i.e., counter clockwise) direction after each encounter. Thus, the position of each successive planet to be encountered relative to the preceding planet in the encounter sequence is not a critical factor. The profile only requires a planetary configuration where each planet in the sequence is leading each preceding planet anywhere from about 10° to about 120° relative to the Sun -- a planetary configuration that does not represent a "rare planetary alignment." And even this configuration is not a necessary condition that must be satisfied. (Pioneer 11 traversed the entire inner Solar System after encountering Jupiter to intercept Saturn on its Jupiter-Saturn leg.)

This fact is illustrated in Fig. 15. The trajectory shown by the solid line represents the Voyager 2 trajectory. The broken lines represent a few of the possible post-encounter trajectories that could be achieved by varying the approach trajectory at each intermediate planet in the encounter sequence. The figure therefore illustrates the wide range of relative planetary positions for Jupiter, Saturn, Uranus, and Neptune that are possible for a realizable Earth-Jupiter-Saturn-Uranus-Neptune trajectory profile.

Gravity Propulsion and Perturbed Cometary Orbits

The concept of gravity-propelled interplanetary space travel is based upon the fact that the orbital energy of a free-fall space vehicle can be changed relative to the Sun without reaction propulsion by a close planetary encounter. However, as was correctly noted in a recent communication from Ruppe,[68] many trajectory engineers working in the 1950s and early 1960s believed that the orbital energy of a free-fall space vehicle must remain constant relative to the Sun, regardless of any planetary encounter. But Ruppe also noted that astronomers working in celestial mechanics knew for at least 100 years that the heliocentric orbital energy of a comet could be changed by passing close to a planet.

Since the innovation of gravity propulsion caused such a profound revolution in the basic technical feasibility of interplanetary space travel, a natural question arises: Since astronomers knew that the orbital energy of a free-fall body could be changed by a close planetary encounter, why didn't they communicate this fact to the trajectory engineers assigned to uncover and determine the interplanetary trajectories for specific missions that require a minimum amount of rocket propulsion so that it could be incorporated into their search? An investigation of this question by the authors revealed some interesting facts. It was discovered that many of the leading theoreticians and astrodynamicists who wrote the research papers and the books that were used to teach trajectory engineers the basic principles of celestial mechanics and astrodynamics were fully aware of this fact. But these leaders, who were often astronomers, nevertheless, still regarded the classical Hohmann trajectory as the "minimum energy" trajectory (or "optimum trajectory") for interplanetary space travel from one planet to another planet and backed up this belief with numerous mathematical demosntrations. For example, Professor Samuel Herrick, who is often cited as being one of the founding fathers of astrodynamics,[126] was fully aware of the fact that the heliocentric orbital energy of a free-fall body can be changed by a close planetary encounter. In fact, Herrick wrote a book on the orbits of comets.[127] However, in 1961 Herrick also wrote a book on astrodynamics that included a detailed mathematical proof demonstrating that Hohmann trajectories represented the minimum energy trajectory for interplanetary space travel from one planet to another planet.[128]

Professors Robert Baker and Maud Makemuson were also leading astrodynamicists who taught this field and wrote the basic textbooks. On page 19 in a section entitled "Perturbations" written in their classic 1960 textbook on astrodynamics,[129] they state: "As the term has been defined in the foregoing, perturbations need not necessarily be small. For example, Comet 1770 Lexell was so accelerated by a close approach to Jupiter in 1779 that it left the Solar System on a hyperbolic orbit and has never been observed again." However, on page 268 of this same textbook, the authors state that Hohmann trajectories represent the minimum energy trajectories required for space travel between two planets and cited Herrick's mathematical demonstration.

Many other similar cases can be cited. But the important point is not the fact that some leading astrodynamicists were aware that the orbital energy of a comet would be changed by a close planetary encounter but rather that they evidently did not connect this effect with the basic problem of space travel. As was pointed out in our first paper,[1] gravitational perturbations were generally regarded as annoying disturbances of two-body (Keplerian) motion, which had to be corrected, often by applying rocket propulsion to cancel out their effect. But even if planetary gravitational perturbations could be used in theory to reduce the propulsion requirements of space travel below the Hohmann limit, using them would require the solution of the Restricted Three-Body Problem, which was unsolved in the early 1960s.[9] However, at the beginning of the 1960s, there was no hint or suggestion that a solution of this problem would result in a significant breakthrough in interplanetary space travel. This absence demonstrates that Minovitch's concept of gravity-propelled space travel was a truly radical innovation in the history and technical development of interplanetary space travel.

Summary

From the inception of space travel in the 19th century to the beginning of the 1960s, it was believed that reaction propulsion, based on Newton's third law of motion, was such a fundamental principle for accelerating a space vehicle relative to a primary inertial frame (the Sun) that it was regarded as one of the most basic principles of space travel. The other assumption that was taken for granted since the 1920s was that Hohmann's trajectory represented the minimum energy trajectory for interplanetary space travel to another planet. Both of these ideas represented the two pillars upon which the technical foundation of interplanetary space travel were laid. But this technical foundation limited the exploration of the Solar System to a very small region because of the inherent limits of chemical rocket propulsion and the technical difficulties of nuclear and electric propulsion (which are still unsolved).

Minovitch's theoretical research during the summer of 1961[1] was significant because it overturned these two principal pillars. His leap from the state of the art, as it existed in 1961, to his vision of gravity-propelled interplanetary space travel was so far and so different from the convential principles of space travel that many professionals regarded it as a violation of the law of conservation of energy. What is most unique about Minovitch's research is the fact that he was involved with astrodynamics for such a short time before he solved one of its most difficult problems -- the Restricted Three-Body Problem -- and that he had the creative insight to recognize that this solution could be used for propelling a space vehicle around the entire Solar System from planet to planet without using any reaction propulsion.

The second important aspect in the early historical development of gravity-propelled space travel was Minovitch's decision to begin a large-scale research project at UCLA to numerically investigate its feasibility after it was rejected at JPL (i.e., JPL's trajectory group) as being impossible. Although Minovitch was unprepared to carry out such an investigation, and had little time for it, he was convinced of its revolutionary potential and worked on it for two-and-a-half years. This research project was funded entirely by the University of California and by the end of September 1964 had consumed over 300 hours of computing time on their IBM 7090/7094 computers.[16,58,111]

The numerical investigation at UCLA began in February 1962. In April 1962, Minovitch informed JPL of his UCLA research project and arranged to have his gravity-propelled multiplanet trajectory program tested with their high-precision interplanetary trajectory integration program.[20] These tests were successful and demonstrated that Minovitch's analytic methods represented the first numerical solution of the unsolved Restricted N-Body Problem of celestial mechanics.[9]

In June 1962, another unusual aspect of Minovitch's UCLA research project began at JPL. Although no JPL or NASA funding was ever given to UCLA to support his research, JPL did give Minovitch direct access to both of their 7090/7094 computers on a time-available basis. This highly unorthodox relationship involving UCLA, Minovitch, and JPL began in June 1962 and lasted through September 1964. Since Minovitch preferred using the JPL computers (especially during the summers of 1962, 1963 and 1964 because he operated them himself), the total amount of computer time consumed at JPL was much more than the total time used at UCLA. Thus, the total amount of computer time used by Minovitch was about 800 hours, making the project one of the most intense non-military computational research projects ever conducted up to that time.

By September 1964, Minovitch's two-and-a-half year research project had demonstrated that his concept of gravity-propelled interplanetary space travel would enable space vehicles to explore the entire Solar System using relatively small conventional launch vehicles such as the chemical Atlas/Centaur. This research eventually led to NASA's Mariner 10 Earth-Venus-Mercury; Pioneer 10 and 11; Voyager 1 and 2; the low launch energy Earth-Venus-Earth-Earth-Jupiter Galileo mission to Jupiter; and the Ulysses out-of-ecliptic solar-polar gravity-propelled missions (and many more that are in the planning stage). The amount of scientific information about the Solar System obtained from these gravity-propelled missions[130] is many times greater than the combined scientific information obtained from all previous conventional missions to Venus and Mars. And this new information came from completely new regions of the Solar System previously believed to be inaccessible with conventional rockets -- the outer Solar System and regions near the Sun itself.

In view of the technical difficulties found in the development of nuclear and electric propulsion systems, these advanced systems were never developed. Thus, Minovitch's contribution to science represented by his innovation and development of gravity-propelled space travel must represent one of the most outstanding individual contributions in science because it made possible the exploration of the entire Solar System.

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