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Chapter 15


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This paper is the third in a series of papers describing the origin of Dr. Michael A. Minovitch’s invention of gravity-propelled interplanetary space travel (gravity-assist trajectories), his early work in developing it, and how the various NASA gravity-propelled missions originated from it. The primary aim of the present paper is to describe the effect of the invention and to show that it was not anticipated. This will be achieved by defining the invention as having two primary components, the use of free-fall multiplanetary trajectories and the use of gravitational perturbations, and showing that each component was proved to be impractical prior to the invention. A technical analysis of the invention is also presented to show that it represented a fundamentally new theory of space travel

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distinctly different from the classical theory based on reaction propulsion developed by Tsiolkovsky, Goddard, and Oberth. It was Minovitch's theory, a mathematical theory of space travel based on finding a numerical solution for the unsolved Restricted Three-Body Problem for motion through the Solar System, and not the classical theory based on reaction propulsion, an engineering theory, that made it possible to break the high-energy barriers of interplanetary space travel and open the entire Solar System to exploration with instrumented spacecraft.

**Introduction**

The history behind the exploration and determination of the structure of atomic and subatomic particles is well known and described in countless science books. The fact that it required the invention of various particle accelerators such as linear accelerators and cyclotrons in order to generate the high kinetic energies is taught in every high school physics class. However, the history behind the exploration and determination of the structure of the Solar System is very hard to find and virtually unknown. Although the accumulated scientific information obtained from the instrumented spacecraft is filling row after row of professional journals in astrophysics, geology, and space science in every large science library, an accurate description of the history behind the technical breakthrough that made it possible to circumvent the classical high-energy barriers of reaction propulsion cannot be found in a single book. This paper, together with our two previous papers,$^{1,2}$ is intended to correct this problem by identifying the key technical papers and references describing the breakthrough.

When the theory of space travel based on reaction propulsion became an engineering research and development effort in the 1930s, it became apparent that only a small fraction of the Solar System could ever be reached with space vehicles. The propulsive energy required to send a vehicle to distant targets in the Solar System was enormous. The problem was that this energy had to be generated off the Earth's surface by an energy-generating system that had to be carried by the vehicle itself (launch system and spacecraft). The relatively low energy densities of chemical propellants required huge amounts of propellant to generate any significant amount of propulsive energy. Unfortunately, this increased the vehicle's inertial mass which required even more energy to overcome. Thus, the exploration of the entire Solar System was believed to be a technical impossibility. A casual investigation of the early history of interplanetary space travel reveals that one of the most famous pioneers who contributed in formulating the basic theory, Professor Hermann Oberth, actually proved that the exploration of most of the Solar System would not be possible.

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With the advent of nuclear power generation after World War II the theoretical possibility of breaking the energy barriers and exploring the entire Solar System changed. If certain technical problems could be solved, it would indeed be possible to explore the entire Solar System. Although the United States spent about two billion dollars over a period of many years beginning in the 1950s in an effort to solve these technical problems, they were too difficult to surmount. (The Soviet Union and other countries also tried to solve the problems, but were also unsuccessful). The required advanced propulsion systems were simply beyond engineering feasibility. When this information became an undeniable fact in the mid-1960s, it appeared that most of the Solar System would indeed remain unknown. However, in a relatively short period beginning in the 1970s, most of the Solar System was explored, and it was achieved with relatively small launch vehicles and conventional chemical rocket propulsion. And this included regions close to the Sun, regions far above and below the ecliptic plane over the Sun’s polar regions, and deep space far beyond the orbit of Pluto. The entire three-dimensional particle and field structure of the Solar System was essentially completely determined. How was this achieved? How was it possible to penetrate one of the most fundamental energy barriers of space science? What was the technical breakthrough that made it possible? The answer to these questions is very simple but virtually unknown. It was achieved by a fundamentally new theory of space travel invented by Dr. Michael A. Minovitch in 1961. It was a mathematical theory of space travel because it was based on finding a numerical solution to one of the most famous unsolved problems in celestial mechanics at that time—the famous Restricted Three-Body Problem for motion through the Solar System.

Although it is never mentioned, there are actually two fundamentally different theories for achieving interplanetary space travel and exploring the Solar System. One theory, based on reaction propulsion, proposed and formulated by Tsiofokov, Goddard, and Oberth (an “engineering theory” using a great deal of hardware and propellant that rapidly increases with vehicle mass) and described in all the history books on space travel which could not generate the high velocities required for exploring most of the Solar System,—and Minovitch’s theory formulated in 1961 (a “mathematical theory” independent of vehicle mass that was a direct result of solving the “Restricted Three-Body Problem”) that did enable the entire Solar System to be explored, but is rarely mentioned or explained in history books.

This is what his invention represented and accomplished, and why it is important to be recognized and understood in the history of space travel. It literally opened up the entire Solar System for exploration with instrumented spacecraft, and it achieved this with relatively small launch vehicles propelled by ordinary
chemical rocket propulsion, and no subsequent reaction propulsion. Thus, it achieved what was believed to be a physical impossibility in 1961. Very few innovations in the history of science have made it possible to break through a fundamental energy barrier, believed to be technically impossible to penetrate, and obtain so much new scientific information for mankind.

Since most of the details of Minovitch’s invention have been covered in our two previous papers, the present paper will be devoted primarily to describing what the invention represented, what it accomplished, and the fact that it was not anticipated. Since the paper is intended to be read independently of our two prior papers, there will be some repetition. However, this will only involve the most fundamental aspects of space travel.

Copies of all the references cited in the present paper, and in our previous two IAF papers, are being placed on file in NASA’s Historical Reference Collection, JPL’s Archives, the IAF Headquarters, Paris France, the Headquarters of the European Space Agency, and at the Japanese Space Agency in Tokyo for unrestricted access to space historians and the general public. It is also available on the Internet at www.gravityassist.com.

The Classical Theory of Space Travel Based on Reaction Propulsion

In order to understand the significance of Minovitch’s invention of gravity propelled interplanetary space travel it is important to understand the classical theory of space travel that existed prior to Minovitch. The underlying theory of space travel formulated by the early pioneers (Tsiolkovsky, Goddard, and Oberth) was based on the principle of “reaction propulsion” using Newton’s Third Law of Motion. Under this theory, a vehicle is propelled by expelling mass at high velocity through an exhaust nozzle. This was achieved by providing a great deal of stored energy (e.g., chemical energy stored in the propellant) and a means for converting this energy into the kinetic energy of the expelled reaction mass. However, this propulsion mechanism added significantly to the vehicle’s total inertia which made it more difficult to accelerate.

The equation that determined the performance of a reaction propulsion system became known as the “rocket equation.” Unfortunately, this equation indicated that the amount of propellant required to achieve a velocity increase \( \Delta V \) increases exponentially with the ratio \( \Delta V/u \) where \( u \) is equal to the exhaust velocity. The equation is usually expressed in terms of the vehicle’s “mass ratio” (initial vehicle mass \( M_i \) divided by the final vehicle mass \( M_f \)) as

\[
\frac{M_i}{M_f} = e^{\Delta V/u}
\]
For chemical rocket propulsion systems, the exhaust velocities \( u \) are limited by basic thermodynamic reasons to rather low values.\(^{11}\) The theoretical maximum is approximately 4.5 km/sec. However, in the 1960s, the maximum achievable exhaust velocities were about 3.5 km/sec. Consequently, if the velocity increase \( \Delta V \) leaving an Earth parking orbit required for injecting an instrumented spacecraft onto an interplanetary trajectory to another planet is high, the required initial mass \( M_i \) becomes far beyond the LEO payload capability of any launch vehicle. The entire technical feasibility of exploring the Solar System with instrumented spacecraft laid down by the early pioneers rested on this equation. It was discovered early on that the launch velocities \( \Delta V \) required for reaching most of the Solar System were far beyond that which could be achieved with chemical rocket propulsion.

**Minimum-Energy Requirements for Exploring the Solar System in the Classical Theory (Hohmann Trajectories)**

The method used for determining whether or not a spacecraft with a given initial mass, equipped with a rocket propulsion system having a certain exhaust velocity \( u \) and propellant mass could be propelled from Earth to reach a certain target planet, involved a procedure that appeared to be so obvious it was accepted as self-evident and never questioned. The procedure involved numerically calculating direct Earth to target planet transfer trajectories, and determining whether or not the required injection velocities \( \Delta V \) departing Earth corresponding to the transfer trajectories could be delivered by the propulsion System.\(^{12-16}\) With this technical procedure accepted as a self-evident starting point since the early pioneers of space travel, Hohmann's cotangential minimum-energy transfer trajectory became one of the most firmly established principles of interplanetary space travel. These minimum-energy trajectories were unperturbed, semi-ellipses with the Sun at one focus tangent to the orbits of the launch and arrival planets. They were discovered by Walter Hohmann in 1925, and became known as the famous “Hohmann trajectories.” (To obtain the absolute minimum-energy, it was assumed that all of the planetary orbits were co-planar).

After Hohmann discovered the trajectory, almost every paper or book published on interplanetary space travel stated that this minimum-energy trajectory is essentially a fundamental law of space travel. References 17-39 provide a small sample of the hundreds of technical papers and scientific books asserting or “proving” the truth of this assumption. Although a few prominent astrodynami-cists (such as Tsander\(^{40}\) working during the 1920s and Lawden\(^{41}\) working during the 1950s) pointed out the theoretical possibility that the propulsion requirements
for space travel could be reduced by taking advantage of gravitational perturbations, these astrodynami-cists still viewed Hohmann’s trajectory as the minimum-energy trajectory relative to the Sun connecting the departure planet (departure planetary system with a moon that might be used), and the target planet (target planetary system with a moon that might be used). And all of this was true provided that the interplanetary portion of the trajectory relative to the Sun was a direct-transfer trajectory which was taken for granted as self-evident. This is the crucial historical fact that must be understood in order to understand the basic innovative feature of the invention of gravity propulsion—it involved the replacement of what was assumed to be self-evident (direct-transfer interplanetary trajectories achieved with a single injection maneuver ΔV out of an Earth parking orbit) with indirect interplanetary trajectories that passed intermediate gravity propulsion planets. All the known astrodynami-cists who pointed out the possibility that gravitational perturbations could theoretically be used to reduce the propulsion requirements for traveling to another planet also constructed mathematical proofs demonstrating that Hohmann’s trajectory is indeed the true minimum-energy trajectory required for interplanetary space travel between two planets. This is the conclusive proof showing that these individuals did not anticipate the invention. In fact, these individuals often referred to the Hohmann minimum-energy trajectories as a “law” of interplanetary space travel. (See pages 240-246 of Ref. 40 and Refs. 18-20). Thus, in view of all the mathematical demonstrations showing that Hohmann trajectories are indeed the true minimum-energy trajectories for interplanetary space travel to another planet, the trajectories became a mathematical certainty. When the numerical values of the orbits corresponding to all the planets were substituted into the corresponding equations for Hohmann trajectories to the planets, it was believed that the resulting numerical values for the minimum launch energies for exploring the Solar System were established with mathematical certainty. These values were published in almost all technical papers and books on space travel. The consequences of this universal belief in the minimum-energy requirements for interplanetary space travel prior to the invention of gravity propelled space travel were that it would not be possible to explore most of the Solar System without developing advanced propulsion systems.

It is important to point out that of the hundreds of technical papers and books written on interplanetary trajectories prior to the invention, it is hard to find any that even mention the possibility that gravitational perturbations could theoretically be a benefit to space travel. The vast majority of the authors of these publications viewed gravitational perturbations from other bodies as annoying disturbances of constant elliptical paths that introduced very complicated analytical
cal problems.\textsuperscript{32,43} (See Ref. 44 and the discussion on page 203 of Ref. 16 to understand how planetary gravitational perturbations on interplanetary trajectories were regarded and treated in guidance algorithms). And those that did still believed that Hohmann trajectories represented the minimum-energy trajectories for exploring the Solar System. Consequently, Hohmann minimum-energy trajectories became one of the most firmly established principles of interplanetary space travel. This is a fundamentally important historical fact that comes directly from the literature and proves that the invention was not anticipated.

**The Unbreakable Launch Periods and the Consequences**

One of the important consequences of Hohmann minimum-energy trajectories to the various planets became known as “launch periods.” These were the periods of time, usually a few weeks long, when the required launch energies for trajectories to a specific target planet were minimum. They were separated by relatively long periods of time equal to the synodic periods of the launch and arrival planets. Since they were determined by the unchangeable orbits of the launch and arrival planets, the launch periods were also believed to be unchangeable.

Launch periods made manned missions to Mars especially difficult because when a vehicle arrives at Mars using a near Hohmann minimum-energy Earth-Mars departing trajectory, a waiting time of 455 days has to be endured on Mars by the astronauts until the next Mars-Earth launch period opens for the return minimum-energy trajectory.\textsuperscript{17,22} A waiting time this long was believed to be beyond the physical endurance of the astronauts. In order to significantly shorten this waiting time, higher energy trajectories were required.\textsuperscript{45} Unfortunately, these higher energy trajectories could only be obtained by nuclear propulsion. (See Ref. 38 and pages 350-385, Ref. 45).

Reaction propulsion, Hohmann trajectories, and launch periods were regarded as the unchangeable fundamental principles of space travel laid down by the early pioneers that were described in almost every book and article written on the subject. The invention of gravity propelled interplanetary space travel formulated in 1961 was important because it overthrew all of these fundamental principles in one sweep.

**The Impossibility of Exploring Most of the Solar System With the Classical Theory of Space Travel**

To explore the entire Solar System, instrumented spacecraft would have to be sent close to the Sun, to all the planets, to regions far beyond Pluto, and to
regions far above and below the ecliptic plane. When the corresponding direct-transfer minimum-energy trajectories were determined, it was found that most of the trajectories were way beyond the reach of chemical rocket propulsion because the required mass ratios were either too high, or the trip times were too long. The only way that the mass ratios could be reduced was by increasing the exhaust velocities \( u \) in the rocket equation. This was viewed as another mathematical certainty that followed directly from this equation which represented the foundation of the classical theory of space travel. Since reaction propulsion was believed to represent the only possible means for propelling a vehicle through the Solar System, there was no other alternative. (It will be shown later that in 1959, Professor Samuel Herrick, another leading astrodynamist at that time, proved that the possibility of utilizing gravitational perturbations to reduce the propulsion requirements for interplanetary space travel envisioned at that time was fundamentally impractical). Thus, it was universally believed that the exploration of most of the Solar System could not be achieved unless advanced high specific-impulse propulsion systems with much higher exhaust velocities were developed.

This can be best documented by citing the words of a few of the leading astrodyna-micists and propulsion engineers at that time. For example, in 1958, Professor Derek Lawden (who was perhaps then the leading theoretical astrodynamist) concluded that (on page 176, Ref. 19):

> “The periods of transit for transfers between the Earth and the outer planets are so great that the cotangential ellipse is unlikely ever to be employed for this purpose. Instead, non-optimal paths involving larger characteristic velocities but shorter periods of transit will have to be followed and, until much higher exhaust velocities become available (e.g., by the harnessing of nuclear energy for rocket motor drives), such journeys will not be possible.”

This statement demonstrates the fact that Lawden did not anticipate the invention.

One of the most well known researchers and authors of books on space travel was Arthur C. Clarke. After spending many years investigating the technical possibilities of exploring the Solar System, he concluded that the energy requirements were far beyond that which could be achieved with conventional chemical rocket propulsion. He described the energy barriers in his book, The Challenge Of The Spaceship published in 1959. Clarke stated (page 55):

> “When today’s chemical fuels have been developed to the ultimate, and such tricks as refueling in space have been fully exploited, we will have spaceships which can attain speeds of about ten miles a
second. That means that the Moon will be reached in two or three
days and the nearer planets in about half a year. ... The remoter plan-
ets, such as Jupiter and Saturn, could be reached only after many
years of travel, and so the trio Moon-Mars-Venus marks the practical
limit of exploration for chemically propelled spaceships.”

Caltech professor and JPL founder Dr. Theodore von Kármán was another
leading figure in astronautics and propulsion technology. He was one of the most
technically qualified individuals in the field of space travel. After studying the
high-energy requirements for reaching most of the Solar System with instru-
mented spacecraft for several years, he concluded in 1962 (page 4, Ref. 47) that:

“It is evident that if we exclude additional propulsion along the tra-
pjector, most of the interplanetary space missions require initial ve-
locities which we are unable to realize by the use of chemical rock-
ets.”

JPL conducted hundreds of mission studies between 1959 and 1964. The
following conclusions, taken from only two, are typical:

“The studies described in this report show that 50% of the unmanned
planetary and interplanetary missions of major scientific interest ex-
amined cannot be performed by chemical systems based on Nova,
and approximately 40% cannot be performed by nuclear heat-
exchanger systems boosted by Saturn S-1” (JPL 1962, Ref. 48 page
9).

“For the scientist interested in a mission to Pluto, preliminary calcu-
lations indicate that not even an all-chemical vehicle as large as the
proposed Nova, and with a flight time of 15 years, could deliver a
payload to Pluto” (JPL 1962, Ref. 49, page 77).

These conclusions were first expressed by the early pioneers of space
travel (Goddard, and Oberth) who studied the mathematical implications of the
“rocket equation,” and realized the limitations of chemical rocket propulsion.
(See pages 1-3, Ref. 50). Professor Hermann Oberth is considered to be one of
the leading pioneers who developed the classical theory of interplanetary space
travel based on reaction propulsion.8 Taking the words directly from Oberth’s
famous book on the possibility of exploring the Solar System published in 1929,
Wege zur Raumschifffahrt, (Ways To Space Travel) the author stated in Section 5
entitled “The Remaining Bodies of our Solar System” (Ref. 51, page 556):
"These cannot be reached with rocket space-ships. .... The three outer planets (Saturn, Uranus, Neptune) and their moons cannot be reached even with the electric space-ship, since the best machines cannot work so far from the sun." (In 1929, prior to the development of nuclear power, the electric generating systems that powered electric space-ships were regarded as solar-electric systems).

Since the technical possibility of exploring the Solar System with instrumented spacecraft was a direct consequence of the underlying astrodynamics and the rocket equation (i.e., the classical theory) it was believed to be unchangeable in the early 1960s. Consequently, since the manned exploration of Mars and the unmanned exploration of most of the Solar System could not be achieved with chemical rocket propulsion, NASA initiated a very large technical effort to develop the systems that were believed to be required—high specific-impulse nuclear and electric propulsion systems. And this belief was regarded as a mathematical certainty. Hundreds of technical papers were published describing this fact. Figure 1 illustrates a representative example of a typical spacecraft design propelled by an advanced high-specific impulse nuclear-electric propulsion system proposed by JPL in 1963 that was believed to be required for breaking the high-energy barriers and exploring the Solar System with instrumented spacecraft.

The Effect That the Invention of Gravity Propelled Space Travel Had on the History of Space Travel

One of the most important facts in the history of space travel is that the advanced propulsion systems were never developed. (And they have still not been developed). By the mid 1960s, after spending over two billion dollars in the effort (and huge amounts by other countries), it became evident that the advanced systems were beyond engineering feasibility. The exploration of most of the Solar System appeared to be beyond technical possibility. One of the most ironic and little known facts in the history of space travel is the fact that the exploration of most the Solar System could not be achieved within the classical theory laid down by the founding pioneers.

But most of the Solar System was explored, and it was carried out with ordinary chemical rocket propulsion and relatively small launch vehicles in a short period of about 35 years. It was accomplished by an entirely new theory of space travel that did not require any reaction propulsion beyond a relatively small
amount used to initiate and maintain the process. This was Minovitch’s invention of gravity propelled interplanetary space travel. This is what the invention accomplished—it made it possible to explore the entire Solar System with instrumented space vehicles. It achieved what was believed to be impossible within the classical theory set forth by Tsiolkovsky, Goddard and Oberth.

![Diagram of a space vehicle](image)

**Figure 1:** Proposed nuclear-electric space cruiser for high-energy missions (From JPL Technical Report No. 32-404 June 8, 1963) (Courtesy of Michael Minovitch).

The gravity propelled trajectories and their names were: Earth-Venus-Mercury (Mariner 10); Earth-Jupiter-Interstellar (Pioneer 10); Earth-Jupiter-Saturn-Interstellar (Pioneer 11); Earth-Jupiter-Saturn-Interstellar (Voyager 1); Earth-Jupiter-Saturn-Uranus-Neptune-Interstellar (Voyager 2); Earth-Jupiter-Out-Of-Ecliptic (Ulysses); and the low launch-energy mission, Earth-Venus-Earth-Earth-Jupiter (Galileo). The combined scientific information obtained from these missions filled many books on astrophysics, space science, and geology, and essentially represented the first detailed information on the structure of the Solar System. There are also new gravity propelled missions such as the Earth-Venus-Venus-Earth-Jupiter-Saturn (Cassini) mission that will enable a spacecraft
to be placed into orbit around Saturn using a relatively small launch vehicle, and the exploration of Pluto using an Earth-Jupiter-Pluto trajectory. And there are other gravity-assist missions to small bodies such as comets and asteroids in various stages of planning.

The invention, therefore, was one of the most important in the history of space travel because it literally made it possible to explore most of the Solar System. It was the invention that broke the minimum-energy requirements set by Hohmann’s trajectory that were previously believed to be unbreakable. It is therefore critically important for the history of space travel to thoroughly document the invention. Minovitch believes that he has a responsibility to accurately explain the historical and technical aspects of the invention and provide this information, along with the all-important documentation, to various archives so that it can be accurately preserved as part of our common space heritage.

Documenting the Invention of Gravity Propelled Interplanetary Space Travel

Although the details and historical circumstances of the invention were explained in our first IAF paper, we shall summarize a few aspects in order to give the reader a basic history of the invention without requiring the reader to read our prior papers.

While working as a graduate student in mathematics and physics from UCLA at the Jet Propulsion Laboratory during the summer of 1961, Minovitch discovered that there was a much more efficient method for propelling a space vehicle through the Solar System than reaction propulsion. It was difficult for propulsion engineers to believe or understand because it was independent of the vehicle’s inertial mass and did not require any propellant or any onboard energy generating system. It was a mathematical method that could be achieved by finding a numerical solution to one of the most famous unsolved problems in celestial mechanics. (Minovitch was preparing for an academic career in mathematical physics at that time and was searching for an important unsolved mathematical problem that he could use for his Ph.D. dissertation). But this problem was very difficult because even some of the world’s best applied mathematicians couldn’t solve it. It was the Restricted Three-Body Problem of celestial mechanics for motion through the Solar System. However, Minovitch recognized that by solving this problem and applying the solution serially to a free-fall vehicle passing a series of planets in a certain order, it would be theoretically possible to propel the vehicle gravitationally relative to the Sun to very high velocities and travel throughout the entire Solar System, passing many planets—that could be ex-
explored during the process—essentially without using any reaction propulsion. (Some reaction propulsion is needed for guidance and course corrections). The idea was to launch a free-fall space vehicle to an easy-to-reach nearby planet using relatively little chemical rocket propulsion, and use the solution of the Three-Body Problem to pass the planet on a precise trajectory such that the planet’s strong gravitational influence would change the vehicle’s orbital energy relative to the Sun and catapult it to another more distant planet, where its gravitational field could then be used to catapult it to another planet, etc. This “planetary billiards” process was self-sustaining and could be continued to achieve space travel with very large velocity changes throughout the entire Solar System that could, in principal, last indefinitely without using any reaction propulsion beyond that required for reaching the first planet and for guidance. Thus, in this mathematical theory of space travel, the propulsive forces are generated by virtue of the vehicle’s own mass via the “equivalence principle,” and the energy required for exploring the Solar System is taken from the Solar System itself. The equivalence principle is the equivalence between inertial mass and gravitational mass. Therefore, in Minovitch’s theory of “gravitational propulsion,” the accelerating forces acting on a vehicle increase automatically in direct proportion to its own inertial mass. The greater the mass, the greater the propulsive force. The mass term cancels out in the equations of motion. Consequently, after the vehicle is injected onto its first leg, it does not matter if the vehicle’s mass is 100 kg or 100 million kg. After the initial injection, both vehicle masses would require essentially the same amount of propellant: zero.

Minovitch documented his theory of gravity propelled space travel in a JPL technical paper dated August 23, 1961. Although most of the paper was mathematical (devoted primarily to finding a close numerical solution to the Restricted Three-Body Problem using new analytical vector techniques that could be used to find the exact solution by a converging numerical integration/iteration process on the differential equations of motion), Minovitch explained what this new mathematical theory of space travel meant with a specific example—a hypothetical gravity propelled trajectory showing how interplanetary space travel throughout the entire Solar System could be achieved without rocket propulsion. This example involved a sequence of seven planetary encounters utilizing the gravitational fields of the inner planets for generating sufficient orbital energy for reaching and utilizing the very large gravitational fields of the outer planets. Quoting directly from page 39 of this paper, Minovitch wrote:

"An example of such a reconnaissance mission may be the following: at \( t_0 \) the vehicle leaves the “center” of the earth and makes a
closest approach to the first planet Venus at time \( t_{1CA} \). It then proceeds to visit the remaining N-1 planets in the following order:
Mars
Earth
Saturn
Pluto
Jupiter
Earth.”

Minovitch concluded the paper with the remarks (page 44):

“In conclusion, we notice the remarkable fact that if \( E \) is the total heliocentric energy of a departing free-fall reconnaissance vehicle to one planet and back, it may be possible to send the vehicle on a trajectory which will take it to N-1 more planets before returning to its launch planet without any appreciable change in \( E \).”

The Evidence Proving That the Invention Was Minovitch’s Original Discovery and Not the Result of Any JPL “Task Assignment”

Since Minovitch had never taken a single course in astrodynamics or engineering when he arrived at JPL in June 1961, and was only working at JPL for a few weeks as a temporary summer employee before he presented his August 23, 1961 paper, it is difficult to believe that he actually made the invention. Most summer employees are given a specific “task assignment” and do not work on research projects not specifically assigned to them. But Minovitch was different. He loved doing original scientific research in addition to his specific task assignments.

The details describing how he made the invention have been described in our first IAF paper\(^1\) and will not be repeated here. However, what is provided in this paper is overwhelming documentary evidence to prove that the invention was indeed Minovitch’s, and not the result of any “JPL task assignment.” One of the primary aims of this paper is to present this evidence.

To show that the discovery of this method of space travel represented a new scientific discovery, and not suggested by anyone at JPL, or part of any “task assignment,” Minovitch explicitly claimed originality on page 1 by writing:\(^8\)

“As far as the author knows the method and results are new.”

This statement proves that the invention was indeed Minovitch’s by the following observation. It was written by a new temporary summer employee at
JPL only two months after beginning work, who was obviously interested in making a good impression. Therefore, if the method of space travel disclosed in the paper was already known at JPL prior to Minovitch's arrival, and that Minovitch was given the "task assignment" to work out the mathematics during the summer of 1961 which resulted in that paper, that statement would have obviously never have been made. If it was a "task assignment," the method of space travel described in the paper was obviously nothing new. It should also be noted that the mathematical problem corresponding to this concept of space travel is extremely difficult and not the sort of problem that would be given to a temporary employee working at JPL on a summer job who was a student who never worked in the field of astrodynamics or celestial mechanics before in his entire life. Figures 2 and 3 are reproductions of pages 1 and 39 of this paper.89

There is a great deal of evidence that conclusively proves it was indeed Minovitch's invention. For example, Minovitch's August 23, 1961 JPL paper was the first documented paper ever written at JPL describing the possibility of replacing a direct-transfer trajectory to a distant target planet with an indirect trajectory that uses intermediate planets as propulsion sources. Clearly, if Minovitch's paper was the result of a "JPL task assignment," there would obviously be some prior documented JPL Report, Technical Memorandum, or some other documented written statement describing the basic idea of using planetary gravitational fields of intermediate planets as propulsion sources for reaching more distant target planets in order to assign Minovitch the task of working out the mathematics. But there is no such prior JPL document.

The evidence is even stronger than this if one carries out an investigation to uncover the first JPL paper ever written by a regular JPL employee pointing out the possibility that the orbital energy of a free-fall spacecraft moving relative to a primary body can be changed by passing close to another body. Obviously, the first JPL document mentioning this fact is the one to uncover and investigate in order to determine whether or not Minovitch's August 23, 1961 paper was the result of any JPL task assignment. The first such paper was published in JPL Research Summary No. 36—13 covering the period December 1, 1961 to February 1, 1962.90 This is critically important because the JPL Research Summaries are publications specifically intended for announcing new developments at JPL as quickly as possible. The first author of this paper (there were two authors) was Minovitch's 1961 JPL supervisor, Victor Clarke, Jr. It was written in January 1962—almost six months after Minovitch presented his August 23, 1961 paper. The paper states the possibility (without any analytical analysis) and describes how it could be applied using the Moon as the perturbing body. It is described in the last sentence in that paper (which was only one page long) with the statement:
“In general, the Moon can be used to add or subtract energy from orbits and to change their planar orientation.”

JET PROPULSION LABORATORY

TECHNICAL MEMO #312-330
August 23, 1961

TO: Section 312 Engineers, J. F. Scott, W. Scholey
FROM: M. A. Minovitch
SUBJECT: A Method For Determining Interplanetary Free-Fall Reconnaissance Trajectories

This paper deals with determining round-trip trajectories for reconnaissance vehicles in free-fall motion when certain fundamental assumptions are assumed to hold. After solving the trajectory problem to one planet and back the more general problem of determining a free-fall reconnaissance trajectory to N planets before returning to the launch planet will be solved. No assumptions will be made as to the geometry of the solar system; indeed, it will not matter how eccentric the planets orbits are or how much their planes of motion differ from each other. Vector analysis is employed throughout the paper giving it a somewhat neat mathematical appearance which should offer interesting reading. As far as the author knows the method and results are new.

The problem of finding an exact analytical solution for round-trip, free-fall reconnaissance trajectories is, to say the least, not trivial. Consequently, in papers treating these problems certain simplifying assumptions are very common. In this paper we shall assume only the most basic:

I. When the vehicle (treated as a particle) is inside a “sphere of influence” \( \gamma \), centered at the center of the target planet, only the field of this body influences its motion. When the vehicle is outside \( \gamma \), only the sun influences its motion.

II. If \( \Delta t \) is the amount of time the vehicle spends in \( \gamma \), \( \Delta t \) is small so that the planet’s motion can be assumed to be constant; its velocity being that velocity it has when the vehicle makes its closest approach.

Before stating the last assumption suppose \( \Sigma \) is some inertial cartesian frame of reference with origin at the center of the sun. Let \( \Sigma ' \) be a moving frame with origin at the center of the target planet and whose axes are kept parallel to the

Figure 2: Reproduction of the first page of Minovitch’s August 23, 1961 JPL paper showing his explicit claim of discovering a new method of space travel (Courtesy of Michael Minovitch).
trajectory of a vehicle launched from the "center" of a given planet at
the prescribed time $t_{02}$, which makes a closest approach to the first
planet to be observed at the prescribed time $t_{14}$ and continue on a
journey of visiting $N-1$ more planets in a prescribed order and return
to the launch planet.

An example of such a reconnaissance mission may be the following:
at $t_{02}$ the vehicle leaves the "center" of the earth and makes a closest
approach to the first planet Venus at time $t_{14}$. It then proceeds to
visit the remaining $N-1$ planets in the following order:

- Mars
- Earth
- Saturn
- Pluto
- Jupiter
- Earth

In this problem we shall make use of the following notation:

(a) $\sum_j^i$ = moving frame of reference centered at center of $j$'th
    planet whose axes are kept parallel to the axes of a primary
    inertial frame $\sum_i$ having origin fixed at center of sun
    ($i = 1, 2, \ldots, N$)

(b) $T_j$ = sphere of influence of $j$'th planet ($j = 1, \ldots, N$)

(c) $\mathbf{r}_{02}$ = position vector of launch planet and initial position
    vector of vehicle at beginning of mission at time $t_{02}$

(d) $\mathbf{r}_{j1}, \mathbf{r}_{j2}$ = position vectors of vehicle as it enters and
    leaves $T_j$ respectively at time $t_{j1}$ and $t_{j2}$ ($j = 1, 2, \ldots, N$)

(e) $\mathbf{\beta}_{j1}, \mathbf{\beta}_{j2}$ = position vectors of vehicle as it enters and
    leaves $T_j$ respectively with respect to $\sum_j$

(f) $\mathbf{c}_{j1}, \mathbf{c}_{j2}, \mathbf{c}_{j3}$ = position vectors of $j$'th planet when vehicle
    enters $T_j$, makes its closest approach, and leaves $T_j$ respectively
    at time $t_{j1}, t_{j3a}$, and $t_{j2}$

Figure 3: Reproduction of page 39 of Minovitch's August 23, 1961 JPL paper describing
an example of his theory of gravity propelled space travel. The example illustrated
how it was possible to explore the entire Solar System using only that amount of
launch energy required for reaching Venus (Courtesy of Michael Minovitch).

It is obvious from this sentence, and the rest of the paper, that the possi-
bility was something new to Clarke, otherwise he would not have explicitly
stated it. If it were a well-known possibility at JPL at that time, he would not
have taken the time to mention something already known. The fact that he did mention it indicates that the possibility was not generally known to members of his Trajectory Group. Thus, this document shows that in January 1962, Clarke was obviously informing his Trajectory Group for the first time about this possibility (i.e., it was something new at JPL). Although Minovitch had his August 23, 1961 paper distributed throughout the entire Systems Analysis Section (Section 312), and tried to get engineers interested in it, there was no interest whatsoever. As described in our first IAF paper, Clarke did not even believe that the concept was theoretically possible at that time (See page 83, Ref. 1). This important historical fact has been corroborated by independent eyewitnesses. (See for example page 76, Ref. 91). It is also important to keep in mind that Minovitch’s 1961 JPL paper was completely unauthorized. He wrote it because he believed that he had solved the Restricted Three-Body Problem (by defining three-dimensional conic trajectories with two constant orthogonal vectors instead of the traditional scalar orbital elements) and had an idea how to use the solution for creating an inexpensive new method for traveling around the Solar System without reaction propulsion. After Minovitch presented his unauthorized paper, Clarke quickly took Minovitch away from the idea and assigned him a problem that had nothing to do with it.

Clarke’s January 1962 paper is also important because it indicates that in January 1962 the theoretical possibility of changing the orbital energy of a free-fall spacecraft by the gravitational influence of another body was new to JPL. These remarks are not intended to detract from Clarke’s technical skills. At that time, most engineers believed that the only way the orbital energy of a spacecraft could be changed was by applying onboard rocket propulsion. This was the commonly held position of the engineering staff and had very important implications. The implications were that Minovitch found it was impossible to convince Clarke and others that the idea was even physically possible and should be numerically investigated at JPL to determine if it had any practical possibilities. JPL had all the computer programming expertise and a giant IBM 7090 computer to conduct the required investigation. Minovitch was not a computer programmer.

Clarke’s 1962 paper is also historically important because it demonstrates that when he finally became convinced that the basic principle was possible, he did not use it as a method for reducing the propulsion requirements for interplanetary space travel as described in Minovitch’s August 23, 1961 paper. Rather, he used it for reducing the propulsion requirements for a few Earth orbital missions. His perturbing body was the Moon, not planets. No mention was made of using it for interplanetary missions. This is what that January 1962 JPL
paper conclusively documents. By that time (January 1962), Minovitch had already started his UCLA research project to numerically investigate his new theory of space travel using UCLA’s large IBM 7090 computer funded by a grant from the University of California. This UCLA research project was greatly expanded when Minovitch requested unlimited computing time which was granted on April 2, 1962. Figure 4 is a reproduction of Minovitch’s proposed UCLA research project that was approved on January 18, 1962. Notice that the title of the proposed UCLA research project was the title of Minovitch’s August 23, 1961 JPL paper. A Method for Determining Interplanetary Free-Fall Reconnaissance Trajectories. JPL was not involved with this UCLA research project and no one at JPL even knew that Minovitch had started it.

FROM: UCLA Computing Facility
TO: Peter Henrici and
    Michael A. Minovitch
    Department of Mathematics
    Campus
Problem No: WALL

Your application for the use of the UCLA Computing Facility
has been approved for researches entitled "A Method for Determining
Interplanetary Free-Fall Reconnaissance Trajectories"
The above problem number has been assigned for this project.

Information concerning use of the IBM 7090 Computer and
auxiliary equipment, as well as the scheduling of time for the
use thereof, is available from J. L. Seifridge or F. H. Hollender.
(Extensions 6644 and 9236 respectively.)

Upon completion of the computations, written notice of the
fact should be sent to the Computing Facility.

Date: January 18, 1962

DIRECTOR, Computing Facility

Figure 4: Reproduction of Minovitch’s proposed UCLA gravity propulsion research project that was approved on January 18, 1962 (Courtesy of Michael Minovitch).
Since the first documented paper ever written at JPL by a regular JPL employee describing the fact that the orbital energy of a free-fall spacecraft can be changed without rocket propulsion by the gravitational influence of a third body did not mention the possibility of applying this principle to interplanetary missions, the next questions that should be asked are: (1) Who was the first regular JPL employee who wrote the first documented paper that mentioned this possibility; (2) what was the date, and (3) what were the specific "gravity-assist trajectories" mentioned. The answer to the first question is again, Victor Clarke, and the date was June 21, 1962.95

On June 21, 1962, Victor Clarke wrote a JPL RFP (Request For Programming) to JPL’s Computing Section (Section 314) to have Minovitch’s IBM 7090 computer program97 duplicated for JPL’s IBM 7090 computers. One of the gravity propelled trajectories singled out in this document was an Earth-Venus-Mars-Earth trajectory (see Ref. 98, and page 1, Ref. 96). This was the first time that this particular gravity propelled (gravity-assist) trajectory was ever specifically mentioned in any documented paper. Furthermore, Minovitch’s UCLA gravity propelled trajectory program that Clarke described in his RFP was capable of calculating any gravity propelled trajectory \( P_1 - P_2 - P_3 \ldots P_n \) where \( P_i (i = 1, 2, \ldots, n) \) represents any planet in the Solar System and \( 3 \leq n \leq 10 \). It represented a new form of interplanetary space travel through the Solar System that did not require any reaction propulsion. That is why Minovitch designed it with the capability of computing gravity propelled trajectories passing many planets. Thus, the first documented paper ever written by a regular JPL employee on the possibility of gravity-assist interplanetary trajectories was an RFP written by Clarke directing their Computing Section to make a copy of Minovitch’s gravity propelled trajectory program that he developed to investigate the concept at UCLA.95

And why did Minovitch undertake this research project at UCLA that was completely outside of his academic field and caused so much disruption in his formal academic work? He did it because he knew it was important and that Clarke refused to conduct any such investigation at JPL because he believed that the basic concept was a physical impossibility. (See pages 83,84 Ref. 1, and page 76, Ref. 91). Figure 5 is a reproduction of the first page of Clarke’s June 21, 1962 JPL RFP.

This is the background describing the first documented paper ever written by a regular JPL employee on the possibility of gravity-assist interplanetary trajectories. It was a directive to JPL’s Computing Section to duplicate Minovitch’s invention without any compensation to Minovitch. (The operational form of the invention was Minovitch’s UCLA’s computer program97). It should also be noted
that when Minovitch began using the JPL computers on a time available basis, he
did not associate himself with Clarke’s Trajectory Group. Rather, he used the
JPL computers attached to JPL’s theoretical group headed by Dr. William Mel-
bourn." (The details of Minovitch’s UCLA gravity propulsion research project
from January 1962 through the end of September 1964 have been described in
our second IAF paper).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>FROM</td>
<td>V. Clarke</td>
<td></td>
</tr>
<tr>
<td>SUBJECT:</td>
<td>Interplanetary Round-Trip Program</td>
<td></td>
</tr>
</tbody>
</table>

1. **INTRODUCTION**

   This RFP is to request two basic actions by Section 372.
   (1) Make Mike Minovitch Round-Trip Interplanetary Trajectory Program operational on the JPL 7090 with minimum modification.
   (2) Follow up action (1) by modifying the program as necessary to meet Section 372 standards and systems requirements. Also, modify output as specified below.

2. **OUTPUT FORMAT**

<table>
<thead>
<tr>
<th>START-VENUS-MARS-EARTH</th>
<th>ARRIVAL DATE</th>
<th>EARTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAUNCH DATE</td>
<td>ECA</td>
<td>C3</td>
</tr>
<tr>
<td></td>
<td>HEL</td>
<td>ECA</td>
</tr>
<tr>
<td>FIRST LEO</td>
<td>INTERCEPT DATE</td>
<td></td>
</tr>
<tr>
<td>ECLIPTIC</td>
<td>TF</td>
<td>RF</td>
</tr>
<tr>
<td></td>
<td>TF</td>
<td>T2P</td>
</tr>
<tr>
<td></td>
<td>I/L</td>
<td>LCP</td>
</tr>
<tr>
<td></td>
<td>VI</td>
<td>V2</td>
</tr>
</tbody>
</table>

**Figure 5:** Reproduction of the first page of Clarke’s June 21, 1962 JPL RFP. This RFP directed JPL’s Computing Section to make a duplicate of Minovitch’s UCLA IBM 7090 gravity propulsion computer program with minimum modification. As indicated in this RFP, Clarke realized the importance of Earth-Venus-Mars-Earth gravity-assist trajectories (Courtesy of Michael Minovitch).
The list below contains, to my knowledge, all of the uncompleted conic RFP's from the Trajectory Group.

<table>
<thead>
<tr>
<th>PROJECT</th>
<th>RFP No.</th>
<th>AUTHOR</th>
<th>TITLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>72A</td>
<td>Clarke</td>
<td>Interplanetary Round Trip Program (i.e. Minovitch type multiple transfers)</td>
</tr>
<tr>
<td>5</td>
<td>135</td>
<td>Clarke</td>
<td>Differential Coefficient Subroutine for the Heliocentric Conic Program (assigned to E. Jacob)</td>
</tr>
<tr>
<td>6</td>
<td>223</td>
<td>Dallas</td>
<td>Computation of Round Trip Trajectories to the Planets ( \text{(torus: impulsive maneuvers at Earth and Target)} )</td>
</tr>
<tr>
<td>3</td>
<td>224</td>
<td>Haynes</td>
<td>Obtaining Conic View Periods Directly from Naco Entries</td>
</tr>
<tr>
<td>4</td>
<td>235</td>
<td>Richard</td>
<td>Direct Ascent Heliocentric Conic Program</td>
</tr>
<tr>
<td>8</td>
<td>287</td>
<td>Richard</td>
<td>Arrival Date as a Parameter in the Naco Plotting Program</td>
</tr>
<tr>
<td>2</td>
<td>301</td>
<td>O'Neil</td>
<td>Modification of NACOM to Target Trajectories Having Specified Injection Path Angles</td>
</tr>
<tr>
<td>1</td>
<td>304</td>
<td>O'Neil</td>
<td>Modification of NACOM to Target on Tracking Station Visibility</td>
</tr>
</tbody>
</table>

All of these programs are desired as soon as possible, and would be in use now if they were available. Thus, they are all of high priority. Please give me an estimate of their completion dates.

We are contemplating additional RFP's, some of which are listed below.

- Wallace: Solar Probe Capability in NACOM
- Wallace: Heliocentric View Period to Punch ProCard
- Wallace: Tracking Angular Rate Limits in View Period
- Burns: Partial Derivatives for Minovitch Trajectories
- Cutting: Earth Position at Launch Rather than O Nore O

Figure 6: Reproduction of a July 13, 1964 JPL Interoffice Memorandum from Elliot Cutting, giving the descriptive titles of various trajectory programs in JPL's Trajectory Group. Note the characterization of "Minovitch-Type Multiplanetary Trajectory Programs." (Courtesy of Michael Minovitch).

Another important fact to be noted, proving that Minovitch's August 23, 1961 paper could not have been a JPL "task assignment," was the fact that JPL did not begin its own gravity-assist mission analysis studies until June 1964.100
(Also see pages 76, 77, Ref. 91). This was three years after Minovitch introduced the concept in his August 1961 JPL paper, and after he gave several technical seminars at JPL and wrote several UCLA, JPL and AIAA technical papers.

There is something else about Minovitch's UCLA gravity propulsion computer program that made it extremely valuable. In April 1962, Gene Bollman (a JPL trajectory analyst) performed several detailed numerical integration/iteration tests on Earth-Venus-Mars-Earth trajectories using the most accurate double-precision interplanetary trajectory integrating program available at that time and found that it represented a numerical solution to the famous unsolved Three-Body Problem of celestial mechanics for motion through the Solar System. (See page 55, Ref. 88, Ref. 101, and page 115, Ref. 102). This was the critical key that transformed the theory from speculation into a realizable new method for achieving high-energy space travel. (Although this detail is rarely if ever mentioned, it was the central core of the invention). Thus, the computer program represented a new form of space travel that JPL could use to break the classical high-energy barriers of reaction propulsion and explore the entire Solar System with instrumented spacecraft. And this is exactly what JPL did. The trajectory program which represented the invention was placed in JPL's inventory of interplanetary trajectory programs and became known at JPL as "Minovitch's Multiplanetary Trajectory Program" for computing "Minovitch-Type Multiplanetary Trajectories."^{93, 104} Figure 6 is a reproduction of a July 13, 1964 JPL Interoffice Memorandum giving the titles of various trajectory programs. Clarke had taken the invention which was Minovitch’s private property and gave it to JPL without compensating Minovitch or UCLA in any manner. This is how JPL acquired the technical means for exploring most of the Solar System. It was definitely not a JPL invention. Although books are being published which describes the invention as a "JPL invention,"^{105} this is definitely not the case. One of the aims of this paper is to provide the detailed evidence substantiating this fundamentally important historical fact.

Unfortunately for Minovitch, Clarke refused to recognize the basic fact that Minovitch had made a truly marvelous and revolutionary discovery that had the potential of changing the history of space travel. Gradually however, Clarke did become aware of this fact. In 1969, Clarke would actually claim that it was his discovery and that he only hired Minovitch in 1961 as his assistant to work out the mathematics.^{106-108} This was the price Minovitch paid for informing JPL of this UCLA research project in April 1962 and using the JPL computers when they were not being used for JPL or NASA projects to increase the scope of his research. (See pages 55-73, Ref. 2). It should also be noted that Minovitch made his UCLA computations available to anyone at JPL that wanted to see them by
having all of his gravity propelled trajectories computed at UCLA delivered to JPL. And the amount was so huge that the stacks of computer printouts had to be delivered to JPL in trucks. The computations started arriving at JPL on May 4, 1962. Hundreds of gravity propelled Earth-Venus-Mars-Earth trajectories were delivered at this time. Minovitch made his UCLA gravity propelled trajectories available to JPL because he realized that they were very important for NASA's space program. Figure 7 is a reproduction of a JPL delivery slip showing the transport of Minovitch's gravity propelled trajectory computations from the UCLA computing facility to JPL using a JPL delivery truck.

**Figure 7:** Reproduction of a May 4, 1962 JPL delivery slip\(^\text{109}\) showing the transport of Minovitch's gravity-propelled trajectory computations from the UCLA computing facility to JPL using a JPL delivery truck (Courtesy of Michael Minovitch).

There is a great deal of additional evidence proving that Minovitch invented gravity-assist trajectories at JPL during the summer of 1961. For example, after JPL started publishing their own papers describing the revolutionary benefits of gravity propelled space travel, Minovitch was identified as the inventor.\(^\text{110}\)
This included the head of JPL's Section 312 (that became the "Systems Division"), who in 1967 was Elliott Cuttng.\textsuperscript{111}

One of the most important papers describing the invention was written by Dr. William Pickering in 1970, who at that time was JPL's Director. Pickering identified Minovitch as the inventor on page 150 of that paper by stating:\textsuperscript{112}

"Six years ago, Minovitch first showed that planetary missions could be made more efficient by using near encounters with other planets to change the heliocentric trajectories. This so-called gravity assist technique is of great value for journeys beyond the planet Jupiter."

In 1971, Dr. C. R. Gates, who at that time was the head of JPL's Systems Division, nominated Minovitch for NASA's highest award—The Exceptional Scientific Achievement Award—for the invention of gravity-assist trajectories.\textsuperscript{113,114} The short citation approved by Gates read as follows:

"For the invention and development of the concept of gravity thrust space flight which form the basis of the multiplanetary missions planned for the seventies. He did the first theoretical and numerical work that demonstrated the many significant advantages of multiplanet travel."

Figure 8 is a reproduction of the actual citation write-up from JPL's Systems Division. Unfortunately, this award nomination for the invention of gravity-assist trajectories was never forwarded to NASA headquarters because, unknown to Minovitch, his 1961 JPL supervisor, Mr. Victor C. Clarke, Jr., was claiming that he was the inventor.\textsuperscript{115,106-108}

In 1974, after Minovitch discovered that Clarke was claiming credit for the invention and informed JPL's Director Dr. William Pickering,\textsuperscript{116-118} Pickering carried out an extensive investigation to determine who really invented gravity-assist trajectories. This investigation revealed that Minovitch was the inventor. This information was put in writing by Clarke, and mailed to Professor Norriss Hetherington in a letter dated July 22, 1974.\textsuperscript{119} A copy of this letter was mailed to Minovitch with a cover letter from Dr. Pickering.\textsuperscript{120} Clarke's letter indicated that the invention was Minovitch's and not his, or the result of any JPL "task assignment." His exact words were:\textsuperscript{119}

"I wish to make it very clear that I did not assign Dr. Minovitch any work on multiple gravity-assist trajectories other than round trip trajectories between Earth and another planet. It is to Dr. Minovitch's great credit that he extended and generalized the problem to gravity-assisted transfers between n bodies in any order."

361
For the invention and development of the concept of gravity thrust space flight which forms the basis for the multiplanet missions planned for the seventies. He did the first theoretical and numerical work that demonstrated the many significant advantages of multiplanet travel.

Figure 8: Reproduction of Minovitch’s 1971 award nomination for the invention of gravity-assist trajectories by the head of JPL’s Systems Division Dr. C. R. Gates. (Courtesy of Michael Minovitch).

Since any task assignment had to come from Minovitch’s immediate supervisor, this letter provides the conclusive proof that Minovitch’s theory of space travel that he disclosed to JPL in his August 23, 1961 paper^9 represented his own discovery. Figure 9 is a reproduction of this letter. Unfortunately, this JPL investigation by Pickering generated a certain amount of hostility against Minovitch which he did not create or deserve. (See pages 73, 78, Ref. 91).

The fact that Minovitch invented gravity-assist trajectories at JPL in 1961 was also confirmed in 1997 by JPL’s Deputy Director Larry Dumas and by JPL’s Chief Scientist, Dr. Mous Chahine. This information was sent to Dr. Minovitch in a letter from Chahine dated November 19, 1997. Figure 10 is a reproduction of this letter.

It is submitted that the above evidence represents overwhelming substantiation that Minovitch’s August 23, 1961 JPL paper^9 represented his own discovery and was not the result of any JPL “task assignment.” An investigation of the scientific literature (which will be presented herein) will show that this paper was the first ever documented disclosing the concept. Therefore, Minovitch is truly the inventor of what is now popularly known as “gravity-assist trajectories.”
Any description of Minovitch's work during the early 1960s as "helping develop the concept at JPL," with the implication that it was invented by someone else as is currently being described in various publications,¹⁰⁵ and over the Internet¹²¹ is grossly inaccurate and very misleading. There was no one "helping Minovitch" work on his 1961 paper,¹⁰⁹ or helping him with his UCLA numerical investigation during 1962-1964. In light of these recent publications, it is important to point out and emphasize that JPL did not begin its own gravity-assist trajectory studies until June 1964.¹⁰⁰ Therefore, there was no one helping Minovitch from JPL before this date.

Dr. Norris S. Hetherington
18 Strong Hall
History Department
University of Kansas
Lawrence, Kansas 66044

July 22, 1974

Dear Dr. Hetherington:

As a result of recent letters written to you and others by Dr. Michael A. Minovitch regarding the accuracy of certain portions of your manuscript entitled, "Gravitational Thrust: The Development and Application of an Idea," I find it necessary to amplify and clarify the comments I made to you on your initial draft. These were made in a letter to you on October 16, 1972, and are noted as reference 20 in your final manuscript.

The question deals with the extent of my work on gravity-assist trajectories and Dr. Minovitch's assignment by me when he began working at the Jet Propulsion Laboratory in June, 1961. I submit for your examination the attached extracts from two JPL Research Summaries.

The first, No. 36-9, describes a portion of my activities from the period April 1 to June 1, 1961, and the second, No. 36-10, covers the following bimonthly period, June 1 to August 1, 1961.

These Research Summaries reflect the fact that I was working on round trip ballistic gravity-deflected trajectories and that I was planning further work on this topic prior to the time that Dr. Minovitch began employment at JPL. That I intended to pursue further work in this area is indicated by another JPL Research Summary, No. 36-11, covering the period August 1 to October 1, 1961. That document shows that another member of my group, Mr. William C. Kirchofer, had done a comprehensive analysis of gravity-deflected trajectories using the Moon as the deflecting body.

I wish to make it very clear that I did not assign Dr. Minovitch any work on multiple gravity-assist trajectories other than round trip trajectories between Earth and another planet. It is to Dr. Minovitch's
great credit that he extended and generalized the problem to gravity-assisted transfers between n bodies in any order. My statement to you in my letter of October 16, 1972, "The substitution of a planet other than Earth for the second planetary encounter was obvious," was transformed in your manuscript into, "... and the extension of the idea to multiple-planet trajectories was obvious." This transformation, plus my use of the trite word, "obvious," conveys an incorrect impression that it was my idea to extend the problem beyond round trip trajectories at the time. Indeed, it was not my idea, but Dr. Minovitch's.

Sincerely,

Victor C. Clarke, Jr.
Mariner 10 Mission Analysis
and Engineering Manager

VCC/Whs
Att.

Figure 9: Reproduction of Clarke's letter of July 22, 1974 admitting that the invention of gravity-assist multiplanetary trajectories during the summer of 1961 was Minovitch's. (Clarke was Minovitch's 1961 JPL supervisor). (Courtesy of Michael Minovitch).

It should be emphasized that Minovitch's research during 1962-1964 was a UCLA research project funded by grants from the University of California. It was never funded or supported by JPL or NASA. By using the JPL computers late at night and during the weekends when they were not being used for JPL or NASA projects, Minovitch was able speed up his UCLA research. Although Minovitch used JPL's secretarial staff to write several technical papers which appeared as JPL papers, the work he did during 1962-1964 was basically a UCLA research project and not a JPL research project. This may be hard to believe or understand but that was how Minovitch conducted the research.

It is also important to emphasize that since Minovitch's formal academic education was in the fields of mathematics and theoretical physics, and not engineering, his concept of space travel was purely mathematical. It was the direct result of formulating a possible numerical solution of the then unsolved Restricted Three-Body Problem for interplanetary trajectories. This was at the heart of the concept. Minovitch recognized that if a solution to this problem could be obtained, it would be possible to calculate the precise approach trajectory at one planet such that its gravitational field would accelerate and catapult a free-fall spacecraft onto a precise interplanetary trajectory to another more distant planet, which itself could be used to repeat the process in a self-sustaining, unending series of planetary encounters with radical trajectory changes relative to the Sun.
Dr. Michael A. Minovitch
Phaser Telepropulsion
1888 Century Park East, Suite 1900
Los Angeles, CA 90067

Dear Dr. Minovitch:

I have enjoyed reading the materials you sent me on October 10, 1997. Although we have not met personally, I am familiar with your work and have followed the development of the elegant gravity-assist trajectories of the JPL planetary missions for many years. I came to JPL from U.C. Berkeley at the end of 1960, a few months before you came as a summer employee from UCLA. Your work became a topic of discussion among many of my colleagues then. All of us then recognized your contribution and we still do.

In your references, I was also pleased to see several citations of your contribution to the development of NASA/JPL missions by JPL, including our Director at that time, Dr. William Pickering. He wrote "Six years ago, Minovitch first showed that planetary missions could be made more efficient by using near encounters with other planets to change the heliocentric trajectories. This so-called gravity assist technique is of great value for journeys beyond the planet Jupiter."

Both NASA and JPL recognized your contribution in 1972 by awarding you a NASA Exceptional Service Award with the citation: "For the first extensive development of the concept of gravity assist trajectories for interplanetary flight. This work involved the basic numerical techniques for analyzing such trajectories and identified multi-planet flight opportunities for Venus, Mercury and Mars."

A more recent acknowledgment occurred in a 1989 JPL publication titled The Voyager Neptune Travel Guide stating (page 104) "Minovitch was the first to show how to design a trajectory to a target planet in such a way that a gravity assist could be obtained from that planet to go on to another planet."

I am sure you will agree that this small sampling clearly acknowledges the great value of your contribution. In addition, our Deputy Director, Mr. Larry Dumes, will have the documents you sent him archived at JPL for future reference and use.

Personally I hope that some day we will have an opportunity to meet and discuss old times.

With my best regards,

Sincerely,

M. T. Chahine
JPL Chief Scientist

Figure 10: Reproduction of Dr. Mous Chahine's letter of November 19, 1997 to Minovitch stating that JPL regards Minovitch as the inventor of gravity-assist trajectories. (Dr. Chahine is JPL's Chief Scientist). (Courtesy of Michael Minovitch).

without any rocket propulsion. Thus, the concept enabled an instrumented spacecraft to be propelled to each planet in the series by using the orbital energy of the proceeding planet instead of sending the spacecraft directly to one target planet from the launch planet using reaction propulsion which turned out to be essentially impossible for reaching the most distant planets with reasonable flight times. By selecting Venus for the first planet (which Minovitch did in his 1961
JPL paper\textsuperscript{28}, it became possible to explore the entire Solar System with an amount of rocket propulsion only required for reaching Venus—the least amount required for reaching any planet. The concept therefore provided a means for breaking one of the most firmly established minimum-energy principles in scientific exploration—Hohmann’s minimum-energy requirements for exploring the Solar System. It became possible to reduce the launch energy for a mission to a distant planet to a small fraction of the energy that was previously believed to be the absolute minimum while simultaneously reducing the required trip time. This is what the invention accomplished—it opened up the entire Solar System for exploration with instrumented spacecraft. It achieved what was believed in 1961 to be physically impossible.

The Evidence Proving That Minovitch’s Invention of Gravity Propelled Space Travel Was Not Anticipated

After our second IAF paper was published in 1991, Mr. Tony Reichhardt wrote an article for the Air and Space Museum of the Smithsonian Institution suggesting that Minovitch’s invention was anticipated by various individuals such as Tsander working in the 1920s, and Lawden working in the 1950s.\textsuperscript{91} Since both of these researchers pointed out the theoretical possibility of utilizing gravitational perturbations, it was suggested that these individuals either originated or anticipated the invention. Others have suggested that Minovitch was anticipated by Hohmann and Crocco since the invention used multiplanetary trajectories which were proposed by both of these individuals. In order to prove that Minovitch’s theory of space travel was not anticipated, we will now present a detailed investigation of these researchers to show that they did not anticipate the invention.

Hohmann’s Multiplanetary Trajectories

One of the reasons why there is confusion regarding the basic novelty of the invention is the fact that it required the use of multiplanetary trajectories, and the fact that multiplanetary trajectories were an old idea. Since Hohmann was the first person to design a multiplanetary trajectory,\textsuperscript{122} it was believed that he was the person who invented “gravity-assisted” trajectories.\textsuperscript{123,124} But the reasons why Hohmann and Minovitch used multiplanetary trajectories were completely different. Hohmann used them as a means for achieving multiplanetary reconnaissance, employing multiple rocket propulsive maneuvers, while Minovitch used
them as a means for achieving multiple propulsive maneuvers gravitationally for radically changing the vehicle's trajectory without rocket propulsion. In other words, Minovitch used them as a means for creating a fundamentally new method for propelling space vehicles through the Solar System. It was a propulsion concept, generated by multiple impulses from a series of planetary gravitational fields, not a reconnaissance concept for observing multiple planets.

In fact, Hohmann regarded planetary perturbations as annoying disturbances of his rocket propelled multiplanetary trajectories. This can be determined by examining Hohmann's own papers. These papers show that not only did Hohmann regard planetary perturbations as annoying disturbances, but he actually canceled them out by using onboard rocket propulsion! Hohmann described the effect of planetary perturbations on a vehicle approaching a perturbing planet on a multiplanetary trajectory, and his method for canceling them out, by stating:

"But since during the initial parallel paths of planet and vehicle orbit interference is unavoidable... Such interference may be obviated by radiating the mass directed against the disturbing planet and equal to the gravitational effect g... The interference correction need not be done in one step, it will be sufficient to do it daily once or several times with corresponding intensity."

Thus, Hohmann's multiplanetary trajectories are clearly not examples of gravity-assist trajectories. Just the opposite is true. He expended a considerable amount of onboard rocket propulsion canceling out the effects of planetary perturbations. When this fundamentally important misunderstanding was uncovered at JPL by the technical staff, and made known to JPL management with a request for permission to publish a correction paper, no correction paper was ever published. Evidently, JPL management did not consider it important. However, the failure to correct this situation in the technical literature had serious repercussions. Since no paper was published providing an accurate description of the invention, the general confusion regarding its basic principles and novelty became very serious in the professional technical journals, and in books written on the history of space travel, which is still continuing almost 40 years after Minovitch made the invention.

Tsander's 1925 Paper Suggesting the Possible Use of Satellite Perturbations

In addition to using multiplanetary trajectories, the invention of gravity propelled interplanetary space travel also used gravitational perturbations, Mino-
vitch's invention was represented by a combination of two distinctly different components: (1) The use of free-fall multiplanetary trajectories; and (2) the use of planetary gravitational perturbations. Consequently, since the possibility of utilizing gravitational perturbations was originally proposed by Tsander in 1925, it was suggested that Minovitch's invention of gravity propelled space travel (gravity-assist trajectories) was an old idea invented by Tsander in 1925.128 The fact that the invention was a combination of two separate components was never mentioned in these arguments. However, since most inventions are represented by two or more components, it is difficult to understand how these arguments could have been put forward and published in the professional literature. But they were. This is the principal reason why Minovitch has been struggling for over 30 years to obtain "official credit" and recognition for his revolutionary invention. One of the principal aims of this paper is to clarify and explain this situation.

In 1925, Tsander wrote a paper entitled "Flights to Other Planets" which contained 9 sections (pages 237-302, Ref. 40). In Section 7 entitled "Flight Around Planet's Satellite for Accelerating or Decelerating Spaceship," he described his idea of the possibility of using gravitational perturbations to reduce the rocket propulsion requirements for interplanetary space travel. In particular, his idea was to use the gravitational perturbations of a moon orbiting a launch planet or orbiting a target planet to reduce the rocket propulsion requirements for traveling from the launch planet to the target planet. However, the interplanetary portion of the trajectory was based on a direct-transfer trajectory. Although Sections 5 and 6 (pages 278-289, Ref. 40) indicate that Tsander was aware of the fact that the orbital energy of a space vehicle could be changed by a close planetary encounter, he states explicitly in Section 1 (page 246, Ref. 40) that a Hohmann direct-transfer trajectory to another planet represents the minimum energy trajectory. Moreover, it should be noted that Tsander was so convinced that the cotangential trajectory (which he derived independent of Hohmann) represented the absolute minimum-energy requirements for planetary exploration that he called the trajectory a fundamental "law of space travel" (see page 246, Ref. 40). Thus, Tsander was also very far from anticipating the innovation. He never mentioned the possibility of reaching a distant target planet by detouring the interplanetary portion of the trajectory around some near-by intermediate planet, and letting the gravitational influence of the intermediate planet catapult the vehicle to the target planet. Tsander never considered the possibility of multiplanetary trajectories. An examination of Tsander's paper reveals that he viewed planetary perturbations as annoying (and dangerous) disturbances that should be avoided since they could throw a vehicle off course from which recovery will be very difficult (page 240, Ref. 40). In view of these facts—easily seen from examining
Tsander’s work—any assertion claiming that Tsander invented or originated what is known today as “gravity-assist trajectories” involving multiplanetary trajectories that is being used for exploring most of the Solar System is incorrect.

Although it may be hard to believe, some professors of astrodynamics are simply ignoring the fact that Tsander never considered multiplanetary trajectories, claiming that he originated what is now known as gravity-assist trajectories.129 How could someone be credited for an invention if he never mentioned one of the most important components?

It should also be pointed out and emphasized that Tsander believed that interplanetary space travel would be conducted by manned space vehicles. Consequently, his interplanetary trajectory designs were all based on round-trip missions. He viewed large planetary gravitational perturbations as very dangerous that could throw a vehicle so much off course that it would never be able to return to Earth.130 He did not foresee interplanetary radio communication, or the possibility of exploring the Solar System with unmanned instrumented spacecraft launched on one-way trajectories.

Lawden’s 1954 Paper Entitled “Perturbation Manoeuvres”

The most important subject involving the technical possibility of exploring the Solar System with space vehicles is the minimum-energy requirements, because they determine the technical feasibility and the size of the required launch vehicles, which are very expensive. Since all of the published papers dealing with this subject prior to Minovitch’s work in 1961 categorically identified Hohmann’s direct-transfer trajectory as representing the minimum-energy trajectory, the innovation was clearly not anticipated. However, in 1954 Derek Lawden published a paper entitled “Perturbation Maneuvers.”41 Since the title suggests he may have anticipated Minovitch’s innovation, it is important to examine this paper in detail. In order to remove any subjective opinions, we shall rely upon Lawden’s own statements to understand his actual thinking on the subject. In the introduction to this paper,41 Lawden makes the following statement:

“A number of writers have suggested that the fuel requirements of a journey between the Earth and the other planets might be reduced by taking advantage of the attractions of various bodies of the Solar System, but the method of calculating such perturbing effects and the economies to be expected do not appear to be widely known. In the next section we shall consider this problem of a space ship attracted by a moving body and will show how to obtain the resulting velocity increment introduced in the ship.”
At the end of the paper in the section entitled “Conclusions and Recommendations,” Lawden states:

“By judicious planning of a journey between two planets, taking advantage of the possible perturbing effects of the many asteroids, a considerable saving in fuel can almost certainly be effected. The manner in which maximum advantage may be taken of the attraction of any such body in the case of a particular journey may be calculated by employing the technique for the discovery of optimal trajectories which has been described by the author elsewhere. This will be the subject of a future investigation. However, a series of numerical investigations of the type explained in this article would act as a very useful basis for this more theoretical research and such work is recommended to those interested in orbital computations.”

In view of these statements, and a close examination of the paper, the following conclusions can be drawn:

1. Lawden mentions the fact that the possibility of utilizing gravitational perturbations for reducing the fuel requirements for traveling to another planet was a previously known concept.

2. The main purpose of the paper was to derive an approximate analytical expression for calculating the velocity increment that a vehicle could receive from a passing body on a journey to another planet, which was not widely known.

3. Lawden views these perturbing bodies as a moon orbiting the departing planet; a moon orbiting the arrival planet; or asteroids moving in interplanetary space between the planets.

Although Lawden does calculate the maximum perturbing effect of Mars (a planet), he makes no statement as to how this particular perturbation could be utilized in the design of interplanetary trajectories taking a vehicle to a more distant target planet. (Since Mars has a relatively weak gravitational field, its effect on an interplanetary trajectory is not very great). At that time, the influence of the gravitational field of Mars (or any other planet) had to be considered in the determination of a special class of trajectories known as free-fall, non-stop, round-trip trajectories such as Earth-Mars-Earth trajectories. But these trajectories do not catapult a free-fall vehicle to a more distant third planet and are obviously not examples of “gravity-assist” trajectories.

Lawden’s suggestion of utilizing the gravitational perturbation of a passing asteroid on a journey between two planets is important because it demonstrates
how far away he really was in anticipating the innovation that involved initially redirecting the trajectory at launch to follow a different interplanetary path to an intermediate "gravity propulsion" planet. The maximum velocity increment that can be received by a passing asteroid is close to zero, and the chances that the asteroid would be in a favorable position on its particular trajectory are also close to zero. If Lawden had substituted "planets" for "asteroids" in his concluding statement, he would have anticipated the invention. But he did not. The substitution of planets represented a fundamentally new idea (detour trajectories on an interplanetary scale) that Lawden clearly did not envision or recognize. This can also be demonstrated by examining his subsequent papers that included the determination of the minimum-energy requirements for reaching and exploring most of the Solar System.19

It is interesting to examine Lawden's papers published after his 1954 paper to determine if his ideas about utilizing gravitational perturbations to reduce the fuel requirements for space travel changed, or approached Minovitch's. They did not. In actuality, Lawden admits that it is not known how gravitational perturbations could be best utilized to reduce the energy requirements for space travel. For example, in a paper published in 1955,19 he states:

"When a rocket is perturbed by a planetary body, a transfer of energy takes place between it and the body which may be to the advantage of the rocket. Thus, by passing close to the Moon, a space ship outward bound from an orbit about the Earth to Mars can acquire a considerable amount of energy without any expenditure of fuel. The best way of utilizing such perturbation effects is not known, although there exist a few purely numerical studies, some of which will be found in Ref. 15 [Lawden's 1954 paper]."

In examining this statement, it is important to note that Lawden's terminology "planetary body" refers to a body in orbit around a planet, i.e., a moon. On page 181 of Ref. 19 published in 1958, he states:

"The way in which maximum advantage may be taken of the attractions of perturbing bodies has not yet been investigated."

On page 52 of Ref. 20 published in 1959 he states:

"Very little investigation has been carried out relating to these maneuvers. The principle is explained in reference [24]. The general theory of optimal trajectories as developed in Section IV embraces such a possibility. The problem is to optimize the position of the attracting body responsible for the perturbation at the instant of depa-
ture. This position on the body’s track can be specified in terms of a single parameter and the given gravitational field structure will then involve this unknown quantity. If it be denoted by \( \kappa \), the theory of Section IV shows how its optimal value may be obtained [Eq.(65)]."

This statement (made in 1959) provides the conclusive technical proof (the mathematical evidence) that Lawden’s idea of utilizing gravitational perturbations of a passing body on the way to a specific target planet was fundamentally different from Minovitch’s. In particular, the statement: “The problem is to optimize the position of the attracting body responsible for the perturbation at the instant of departure,” proves that the trajectory was implicitly designed to be a free-fall direct-transfer trajectory from the launch planet to the target planet where the possible perturbation effects of any perturbing body close by could be optimized by varying the launch time. This is the only way that the position of the perturbing body relative to the free-fall trajectory can be “optimized.” Thus, Lawden’s interplanetary trajectories to a target planet using possible gravitational perturbations were designed as direct-transfer trajectories from the launch planet to the target planet. The reason why Lawden did not explicitly state this fact was because at that time, that is how everyone designed interplanetary trajectories. It did not have to be stated. This demonstrates that the substitution of a direct-transfer trajectory to a target planet with an in-direct trajectory passing one or more intermediate gravity propulsion planets was a radically new innovation.

Since Lawden constantly refers to his 1954 paper\textsuperscript{41} in these articles, it demonstrates that his basic conceptual thinking on the possibility of utilizing gravitational perturbations did not change, except in one important respect. He correctly deleted mentioning the possibility of utilizing perturbations from asteroids. His perturbing bodies were moons which he called “planetary bodies.” Thus, by 1959, his views on the possibility of utilizing gravitational perturbations to reduce the propulsion requirements for space travel became identical with those expressed by Tsander.\textsuperscript{40}

Lawden’s views on the influence of planetary perturbations on interplanetary trajectories can be obtained from his papers on navigation and guidance where he was quite specific. For example, in his 1960 paper\textsuperscript{44} entitled “The Theory of Correctional Maneuvers in Interplanetary Space,” he designed his interplanetary trajectories as having three parts: (a) the trajectory in the vicinity of the departure planet, (b) the interplanetary portion, and (c) the portion in the vicinity of the target planet. The interplanetary portion (b) was designed to be a constant elliptical path (a Keplerian arc), which, quoting directly from Lawden:\textsuperscript{44}
“It follows under the attraction of the Sun alone.”... “In this paper, therefore, attention will be given to the main problem of computing any correctional thrusts which may become necessary during the motion along the arc (b).”

Thus, Lawden viewed planetary perturbations as annoying disturbances of interplanetary trajectories taking a vehicle from one planet to another that had to be corrected by onboard rocket propulsion. There is no hint of the possibility of detouring the interplanetary flight path to an intermediate planet to receive large perturbations that could catapult the vehicle to the target planet indirectly.

Perhaps the most conclusive evidence that proves definitively that Lawden did not anticipate Minovitch’s invention is the simple fact that Lawden never published a single paper on free-fall multiplanetary trajectories—which is an indispensable feature of gravity propelled interplanetary space travel—prior to Minovitch’s work in 1961. The literature indicates that Lawden never published a single paper dealing with multiplanetary trajectories (much less gravity propelled multiplanetary trajectories) during his entire career.

**The First Free-Fall Multiplanetary Trajectory Was Proposed in 1956 by Crocco**

In 1956, G. Crocco discovered an unusual constant elliptical path with timing characteristics that would take a non-stop free-fall reconnaissance vehicle past the orbits of Mars and Venus just as these planets arrived, and return it to Earth with a period of exactly one year. The idea behind this trajectory was the same as Hohmann’s multiplanetary trajectory. It enabled one vehicle, in one mission, to make a reconnaissance of two different planets. However, Crocco’s trajectory design was a nonstop free-fall flyby trajectory based on a synchronization principle that had the form Earth-Mars-Venus-Earth. Unfortunately, the gravitational perturbations of Mars and Venus destroyed the synchronization required to achieve the last two planetary interceptions after passing Mars. To solve this perturbation problem, Crocco used the Venus perturbation to cancel out the effect of the Mars perturbation in order to obtain a final trajectory close to his ideal unperturbed constant elliptical path. Quoting directly from the abstract of his paper, Crocco states:

“First of all, the case with no planetary perturbations is taken into consideration, and a possible ideal solution is determined. Subsequently, the perturbation due to Mars by passing at a short distance from it is introduced and the delay attained there to in the trip time is computed. Then, the perturbation due to Venus is examined, and re-
quirements of flights at a short distance are determined capable of correcting the perturbation due Mars.”

Thus, Crocco specifically designed his trajectory to cancel out the effects of gravitational perturbations to obtain a nearly constant elliptical path with a period close to one year to enable the vehicle to return to Earth. Since the mass of Venus was greater than the mass of Mars, Venus had to be encountered after Mars in order to correct the effect of the perturbation of Mars. Thus, the trajectory had to be designed as Earth-Mars-Venus-Earth instead of Earth-Venus-Mars-Earth. It is quite apparent that Crocco viewed the planetary gravitational perturbations during the flybys as annoying disturbances that tended to destroy his synchronous constant elliptical path with a period of one year. He designed his free-fall multiplanetary trajectory using principles as far away from gravity propelled trajectory design as possible. As a result, his trajectory required a launch hyperbolic escape velocity \( V_e = 11.7 \text{ km/sec} \) because the departing trajectory left the Earth’s orbit at a fairly steep angle. (See page 190, Ref. 24). However, if Mars and Venus are switched in the encounter sequence to Earth-Venus-Mars-Earth, and the trajectory is designed using the concept of gravity propulsion, the departing Earth-Venus leg can be almost tangent to the Earth’s orbit so that \( V_e \) can be reduced to only about 3.5 km/sec. This change represents a *tenfold reduction in the required launch energy* \( (V_e)^2 \). But Crocco never mentioned this gravity propulsion concept based on changing the initial leg of the trajectory. His underlying trajectory design methodology was based on finding a constant elliptical path (which he called the “ideal path”) that would intercept Mars and Venus, and canceling out the effects of gravitational perturbations that would destroy the timing requirements for achieving the encounters. The novelty of his paper was the discovery of the unique elliptical path that intercepted both Mars and Venus and how it could be achieved by *eliminating* the effects of planetary gravitational perturbations.

This paper is important in understanding the invention of gravity propelled space travel because it established an absolute lower bound on the date of the invention. Since one of the important components of the invention was the use of non-stop, free-fall, multiplanetary trajectories, the invention had to occur after 1956. Therefore, this establishes the fact that Tsander, Hohmann, and Lawden did not invent gravity-assist trajectories.

The second important component of the invention involved utilizing planetary gravitational perturbations to *change the initial launch trajectory*. Since Crocco explicitly stated in his abstract that his multiplanetary trajectory was designed by eliminating the effects of gravitational perturbations, Crocco’s trajectory is not an example of gravity propelled trajectory design. In view of Crocco’s
explicit statement of eliminating the effects of planetary gravitational fields in order to *maintain the initial launch trajectory*, (which he called the “ideal” trajectory which required enormous launch energy) it is difficult to understand how papers could have been published in technical books and leading professional journals by professional astrodynamists claiming that Crocco’s Earth-Mars-Venus-Earth multiplanetary round-trip trajectory was an example gravity-assist trajectory design.\textsuperscript{126,133,134} But they were, and they had an enormous effect on Minovitch’s struggle to obtain “official credit.” These papers, along with those giving the credit to Hohmann, Tsander and Lawden created the so-called “controversy,” “confusion,” and “misunderstanding” that is still going on among some professional astrodynamists.\textsuperscript{91,129} Minovitch cannot understand how this confusion can still be going on after almost 40 years since he made the invention, and after the literature proves conclusively that these individuals did not make the invention, and were not even close to the invention. But this is what happens when papers attempting to describe the historical and technical facts behind the invention cannot be published in the professional literature.\textsuperscript{125}

**The Invention Was Not Anticipated by Science Fiction Stories**

Some authors have suggested that the innovation was not new because it was anticipated by certain science fiction novels. For example, in the previously cited article by Reichhardt,\textsuperscript{91} the author cites a novel written by Lester del Rey in 1939.\textsuperscript{135} The story describes an interplanetary journey where Jupiter’s gravitational field is used to change the direction of a space vehicle’s path without rocket propulsion. To support his contention that the concept of gravity-assist trajectories was an old idea, Reichhardt cited a specific passage:

“That’s what I’d been looking for, something to catch hold of out in space to swing me around without loss of momentum, and that’s what I’d found: Jupiter’s gravity pulled me around like a lead weight on a swing rope.”\textsuperscript{135}

But the phrase “without loss of momentum” does not state that the vehicle’s momentum (or orbital energy relative to the Sun) can be changed by the encounter, which is the basis of gravity-assist trajectories. On the contrary, the cited passages describe a completely opposite effect—that Jupiter’s gravitational field can be used such that the vehicle can proceed without any change or “loss of momentum.” The effect of using Jupiter’s gravitational field in this example actually shows that there is no change in momentum (i.e., no gravity-assist).

A more serious attempt to use a science fiction story as a basis for suggesting that gravity propelled space travel was an old idea was put forward by Robert
Powers in his book on the history of space travel published in 1978, entitled *Planetary Encounters*. Powers actually gave the credit for originating the concept of gravity-assist trajectories to Arthur C. Clarke on the basis of dialogue Clarke wrote in a 1952 science fiction novel entitled, *The Sands of Mars*. On page 127 of that novel, a non-stop, multiplanetary flyby mission involving Jupiter and Saturn was described in a fictional conversation between two characters in the novel. One person told the other that when a space vehicle approaches Jupiter, its gravitational field can swing the vehicle around such that it departs in a direction to Saturn. The basis for the assignment of credit was the single sentence:

“We go rather close to Jupiter—right inside all the satellites—and let his gravitational field swing us round so that we head out in the right direction for Saturn.”

Note the conspicuous absence of any statement describing the possibility of changing the vehicle’s speed (or orbital energy) relative to the Sun as a result of the encounter with Jupiter, which is the underlying principle of gravity-assist trajectories, and is the reason for making a detour around an intermediate planet on the way to a target planet. Clarke obviously did not recognize that a change in direction could result in a substantial increase in the vehicle’s speed relative to the Sun. If there is no change in speed relative to the Sun by passing Jupiter (no propulsive effect), a trip to Saturn via Jupiter would have no propulsive advantage and would only result in a substantial increase in trip time due to the increased distance that must be traversed because of the detour. There would be no reduction in the required launch energy departing Earth. However, in citing Clarke’s 1952 novel as the basis for the assignment of credit, Powers stated that Clarke used the idea for a mission to Saturn with a “gravity slingshot off Jupiter.” But after examining the evidence, we find no such statement or description in Clarke’s sentence, or in the entire book. Thus, in this example, credit for the invention was given to a person (A. C. Clarke) through a major publication on the history of space travel solely on the basis of dialogue published in a science fiction book *that didn’t even describe the invention and on the basis of dialogue added by Powers that Clarke never even put in the book.*

In 1930, Ray Cummings published his science fiction novel entitled, *Brigands of the Moon* in *Astounding Stories*. He described how the gravitational perturbations of the Moon can be used to reduce the propulsion requirements for a trip to Mars. Quoting directly from this novel we find the passages (page 318):

“We were at this time no more than some sixty-five thousand miles from the moon’s surface. The Planetara presently would swing upon
her direct course for Mars. There was nothing that would cause passenger comment in this close passing of the moon; normally we used the satellite’s attraction to give us additional starting speed.”

However, since the possibility of utilizing the gravitational influence of the Moon was proposed several years earlier by Tsander, the novel did not describe anything new. As will be shown later in this paper, the possibility of using the gravitational perturbations of the Moon were proved analytically to be impractical in 1959 by Professor Samuel Herrick. It is important to emphasize the fact that prior to Minovitch’s invention, the particular method that was envisioned in the possibility of utilizing gravitational perturbations assume that the perturbing body was the Moon, or another moon orbiting a target planet.

The important observation that should be made from these cases is not the fact that the cited science fiction stories do not use or introduce the principle of gravity-assist trajectories, but the very sad fact that science fiction stories are used in an attempt to support a position that cannot otherwise be supported by the scientific literature. Science fiction stories are not a valid criterion for establishing the originality of an invention, or a time frame in which it was first used.

**Round-Trip Free-Fall Trajectories to a Single Planet Are Not Examples of Gravity-Assist Trajectories**

Another example put forward to claim that gravity-assist trajectories were nothing new involved conventional single-planet, round-trip, non-stop, free-fall, trajectories, where the gravitational influence of the target planet is used to “deflect” the vehicle back to Earth without rocket propulsion. Although this argument appears to be convincing at first glance, a close examination of round-trip trajectories reveals that they are not examples of “gravity-assist trajectories” in the usual technical meaning of that term. (The terminology “gravity-assist trajectories” describing the invention was coined in 1966). Since round-trip trajectories are designed to take a vehicle to a target planet on a direct-transfer route, there is obviously no reduction in the amount of launch energy required to reach the target planet. In addition, the post-encounter trajectory is designed to bring the vehicle back to Earth along a free-fall path with or without using the gravitational influence of the target planet. The fact of the matter is that when the condition of a round-trip free-fall requirement is placed on the overall trajectory design for a mission to a target planet, the amount of launch energy required to reach the target planet is always greater than that required for a simple one-way trajectory. Consequently, since round-trip trajectories to a target planet always require more rocket propulsion than a simple one-way trajectory, they cannot be viewed as an
example of "gravity-assist" trajectory design since the essence of gravity-assist trajectories is to reduce the amount of rocket propulsion required to reach the target planet. Obviously, it is not possible to utilize the gravitational perturbations of a target planet to reduce the launch energy required to get there.

The invention of gravity assist trajectories reduces the launch energy by utilizing the gravitational fields of intermediate planets. There are no intermediate planets in round-trip trajectories to a single planet. It must be emphasized that the invention involves a particular method for utilizing gravitational perturbations, and not the fact that gravitational perturbations can be utilized.

Strictly speaking, since the gravitational influence of the target planet is used in determining round-trip free-fall trajectories, it can be said that round-trip free-fall trajectories to a single target planet is an example of gravity-assist trajectories. But it is not an example of Minovitch's invention of gravity propelled interplanetary space travel. The confusion is due to the fact that the terminology "gravity-assist trajectories" is not precise enough to be a good description of Minovitch's invention. It is too broad, thereby enabling an argument to be made contending that "gravity-assist trajectories" were designed prior to Minovitch's work in 1961, which is incorrect and misleading. Minovitch created a new theory of space travel that can be precisely defined as a free-fall multiplanetary trajectory passing n - 1 planets P_i, represented by P_1 - P_2 - P_3 - ... - P_n where i = 1, 2, 3 ..., n, and n ≥ 3 where the gravitational influence of each passing planet is used to radically change the launch trajectory relative to the Sun thereby enabling a vehicle to be propelled throughout the entire Solar System without rocket propulsion and independent of its inertial mass. The propulsive forces are generated at various planets thereby enabling the reconnaissance of these planets while undergoing vehicle propulsion. The simplest form is P_1 - P_2 - P_3 where P_3 is the target planet that is not the launch planet P_1 and is reached by the gravitational influence of the intermediate gravity propulsion planet P_2.

**Gary Flandro's Assignment of Credit to Krafft Ehricke**

In a 1997 published interview with Professor David Swift from the Department of Sociology at the University of Hawaii, Gary Flandro contends that Minovitch’s invention was anticipated by Krafft Ehricke and cited his book *Space Flight, Vol. II, Dynamics*. (See pages 62-74, Ref. 141). However, a careful examination of this book reveals that Ehricke wrote the Preface in October 1962. (See page xvi, Ref. 28). Minovitch wrote his paper *August 23, 1961*. It is difficult to understand how Flandro could assign the credit to Ehricke on the basis of
publication written over one year after Minovitch wrote his paper. Therefore, this assignment of credit to Krafft Ehricke is clearly not valid.

It is interesting to examine some of the evidence Flandro presents in citing Ehricke’s book. In particular, Flandro cites a sentence written by Ehricke on page 31 in the Preface. The sentence that Ehricke actually wrote reads:

“The important implications of a hyperbolic encounter on control of the post-encounter orbit in the higher-order central force field are discussed in detail, since hyperbolic encounter represents a potentially important means of central force field orbit change without propellant expenditure.”

In the published interview with Professor Swift, Flandro changed the last part of the sentence to read:

“... hyperbolic encounter (with an intermediate planet) represents a potentially important means of central force field orbit change without propellant expenditure.”

Notice that the actual sentence Ehricke wrote does not describe or involve a multiplanetary trajectory passing an “intermediate planet” were the gravitational perturbations of the “intermediate planet” is used to reach another planet without propulsion. Ehricke’s book was 1,210 pages long and there is no description anywhere in this book describing the possibility of using the gravitational field of one planet, “an intermediate planet,” to send a free-fall vehicle to another planet. However, after Flandro altered the sentence, it would appear that Ehricke was describing a trajectory that uses the gravitational influence of an “intermediate planet” to propel a free-fall vehicle to another planet without propulsion, which is the basic idea of “gravity-assist trajectories.” Therefore, this is another example demonstrating how words were actually added to a sentence that were never originally written in an attempt to prove that Minovitch’s invention was anticipated.

Ehricke did describe in great detail on pages 1058-1070, how he actually designed multiplanetary trajectories, and how he actually regarded and treated the effects of planetary gravitational fields (gravitational perturbations) from the intermediate planets on these trajectories. Ehricke entitled this section of this investigation: *Interplanetary Flights Involving Several Planets*. On page 1062 in this section, Ehricke states:

“Perturbations by the planetary encounter are assumed to be corrected, preferably while nearest to the planet so that a heliocentric el-
ellipse closely resembling the original ellipse is resumed by the time the vehicle is sufficiently removed from the planet."

Thus, contrary to Flandro’s claim, Ehricke actually treated the effects of planetary perturbations from the intermediate planets in multiplanetary trajectories as annoying disturbances that had to be canceled out by onboard rocket propulsion. This is conclusive evidence proving that Ehricke did not invent, use, or recognize the benefits of “gravity-assist trajectories” as claimed by Flandro. On the contrary, this sentence proves that Ehricke regarded the most important element of gravity-assist trajectories, namely planetary perturbations, as annoying disturbances that had to be “corrected” and used onboard rocket propulsion to carry out this correction. It should also be noted and emphasized that Ehricke’s book was one of the most popular instructional textbooks for teaching the field of astrodynamics in the 1960s.

It should also be noted that Flandro also cited pages 1107-1109 in Ehricke’s book illustrating how the gravitational field of Jupiter can be used for propelling a free-fall vehicle into deep space. What Flandro failed to mention was that the initial Earth-Jupiter launch trajectory departing Earth that Ehricke used was a parabolic solar escape trajectory requiring a hyperbolic excess velocity of about 12 km/sec. In the early 1960s, hyperbolic excess velocities departing Earth this high were essentially impossible to achieve. (See page 77, Ref. 49). Flandro also stated in the interview with Professor Swift. (See page 62, Ref. 141):

“I used Ehricke’s works in all of my mission analysis efforts at JPL and was greatly inspired by them as I began my quest for trajectories to Jupiter and beyond.”

However, an examination of Flandro’s first paper reveals that he made no mention of Ehricke’s work. The first two references cited by Flandro were Minovitch’s two JPL Technical Reports. The first Report described the theory of gravity propelled interplanetary space travel and the vector methods that he developed to analytically determine these very complicated trajectories. Section III of this Report was entitled, Using the Gravitational Influence of a Passing Planet. In describing the theory behind this concept (gravity-assist trajectories), Minovitch explicitly claimed the credit on page 9 in a footnote stating:

“Proposed as a means for meeting energy requirements (see Ref. 2).”

Ref. 2 in this citation was his August 23, 1961 JPL paper. It is difficult to understand how Flandro could have ignored this critically important historical information (or take the time to at least investigate it).
The second Minovitch Report\textsuperscript{145} cited by Flandro in his paper gave detailed planetary configuration diagrams showing the relative positions of all the outer planets for the period 1967-1978. (See pages 57-76, Ref. 145). Superimposed on these configuration diagrams were Jupiter-propelled post-encounter trajectories passing the orbits of all the outer planets, corresponding to various Earth-Jupiter launch periods. These diagrams enabled the various encounter sequences connecting the outer planets to be identified by simple inspection. (Flandro has a different story; see page 65, Ref. 141).

The computer program that Flandro used to compute these trajectories was also Minovitch’s UCLA program.\textsuperscript{97} It was the only computer program at JPL that could compute gravity-assist trajectories. It was known at JPL as the “Minovitch-Type Multiplanetary Trajectory Program.”\textsuperscript{103,104} This program was sent to Lockheed by Victor Clarke in 1962 to enable Stanley Ross and his group to compute what became known as the “Venus Swing-by Mode in Missions to Mars.” (See Ref. 146, and pages 8 and 10, Ref. 118). Flandro was not given his assignment to compute gravity-assist trajectories involving the outer planets until the summer of 1965. He was given the assignment by Elliott Cutting who headed JPL’s trajectory group at that time.\textsuperscript{147} He never worked at JPL in this new field prior to the summer of 1965. (Flandro gives a different story on pages 62 and 64, Ref. 141). Minovitch was not at JPL during 1965, and never met Flandro in his entire life. (See pages 91-93 of Ref. 2). Apparently, an effort has been made to place Minovitch at JPL working on Jupiter gravity-assist missions at the same time Flandro was. But this is not true. (See page 80, Ref. 141). Minovitch completed the research involving Jupiter generated gravity-assist trajectories in September 1964 not 1965, and Flandro was given the results of Minovitch’s 1964 work when he began his work during the summer of 1965. Figure 11 is a reproduction of Cutting’s letter informing Minovitch that JPL is developing considerable interest in his gravity assist trajectories to the outer solar system via Jupiter and will continue the work during the summer of 1965.\textsuperscript{147}

For many years after completing his assignment, Flandro gave the credit for the invention of gravity-assist trajectories to Walter Hohmann. (See Ref. 123 and page 96, Ref. 126). It is difficult to understand how Flandro could give the credit to Hohmann when Hohmann explicitly stated that planetary perturbations were annoying disturbances of his multiplanetary trajectories that had to be canceled out by using onboard rocket propulsion.\textsuperscript{121} But he did. Moreover, JPL is publishing this misinformation in prestigious encyclopedias devoted to space science even at the present time\textsuperscript{148} long after JPL’s own technical staff informed JPL management that Hohmann did not originate gravity-assist trajectories.\textsuperscript{125}
May 21, 1965

Mr. Michael A. Minovitch
International House
Room 746
University of California
Berkeley 4, California

Dear Mike,

In accordance with our conversation this morning, a preliminary copy of your report is enclosed. The final version will be bound with plastic, have a special cover, and be improved in other ways. We have retained the original typed copy to avoid any possibility of loss in the mail. Your manuscript is being returned in a separate envelope.

Will you please make corrections and return the report to me as soon as possible. We have noticed several possible corrections such as:

1. Equation numbers are needed in several places both on the equation itself and in the text.
2. Are the planetary encounter figures complete?
3. In Fig. 1, should the ordinate by $W_2/W_1$ rather than $W_2/W_1$?

As soon as the report is complete, I will send you some copies. There is a good possibility that, in the future, we will want to republish the report as an external Technical Report rather than an internal Section 312 Technical Memorandum.

The report is of considerable current interest at JPL. We intend to do an advanced mission study of a deep space probe this summer. Your report will be very useful for this study. That is one reason why I am anxious for you to complete the corrections as soon as possible.

If you change your address this summer, please let me know. Call me collect to area code 213, 354-4908. If you are in this area please stop by and see us. I believe your report is a fine piece of work and wish you could be here this summer to continue the work.

Sincerely yours,

E. Cutting

Enclosure

Technical data

Telephone 354-4908

Figure 11: Reproduction of Elliot Cutting’s May 21, 1965 letter informing Minovitch that his report on Jupiter propelled trajectories throughout the entire Solar System has generated considerable current interest at JPL and that he intends to begin further studies of Jupiter propelled deep-space missions during the summer. The letter indicates that Cutting had not yet assigned anyone to carry out the work at that time and that Minovitch’s Report will be very useful. (Courtesy of Michael Minovitch).
It should also be noted that Krafft Ehricke’s investigation of the effects of gravitational perturbations on trajectories that Flandro was referring to was based on two-dimensional analysis and therefore not applicable to three-dimensional multiplanetary gravity-assist trajectories. But this is a moot point having no relevance because all of the gravity-assist multiplanetary trajectory computations that Flandro performed during his 1965 work assignment were done with Minovitch’s pre-existing gravity-assist trajectory program that was operated under closed shop conditions. (See Ref. 143 and page 97, Ref. 126). All that was required to compute the various trajectories was imputing the initial parameters (launch periods) and the planetary encounter sequences. This computer program did all of the numerical work automatically. No analysis or trajectory design was required. For example, the planetary configuration for the 1977 Earth-Jupiter launch period (see page 74, Ref. 145) indicated that the following encounter sequences were possible: (1) Earth-Jupiter-Saturn; (2) Earth-Jupiter-Uranus; (3) Earth-Jupiter-Neptune; (4) Earth-Jupiter-Pluto; (5) Earth-Jupiter-Saturn-Uranus; (6) Earth-Jupiter-Saturn-Neptune; (7) Earth-Jupiter-Saturn-Pluto; (8) Earth-Jupiter-Saturn-Uranus-Neptune; and (9) Earth-Jupiter-Uranus-Neptune. The numerical determination of all these trajectories can be easily obtained in one computer run by simply setting the mission matrix $NP(i,j)$ (the input data for the computer program$^{97}$) equal to:

$$
\begin{align*}
3 & 5 & 6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 5 & 7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 5 & 8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 5 & 9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{align*}
$$

$$
NP(i,j) = \begin{align*}
3 & 5 & 6 & 7 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 5 & 6 & 8 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 5 & 6 & 9 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 5 & 6 & 7 & 8 & 0 & 0 & 0 & 0 & 0 \\
3 & 5 & 7 & 8 & 0 & 0 & 0 & 0 & 0 & 0
\end{align*}
$$

By selecting the time intervals between successive launch dates, and the Jupiter arrival dates, it is possible to compute a few trajectories of each type, or many hundreds. The important point to be emphasized here is the fact that the computer does all of the numerical work. (Every trajectory that Flandro described and computed in his paper corresponding to the 1977 launch period can be completely determined by the single computer run having the above mission matrix for the input data). The various encounter sequences are identified (i.e., “discovered”) from the configuration diagrams, and not with the computer. Thus, the process of identifying the possible encounter sequences from the diagrams, and loading the corresponding row vectors into the mission matrix for the numerical
determination was very simple and straight-forward. Once the idea is known, scanning the configuration diagrams and identifying possible encounter sequences corresponding to various Earth-Jupiter launch periods is not difficult—especially if the configuration diagrams have already been constructed and the computer program is made available. (See pages 58-76, Ref. 145).

These remarks are not intended to detract from Flandro's fine work, but rather, to describe it accurately for the historical record. The interested reader should obtain a copy of Flandro's first paper, along with copies of Minovitch's two JPL Technical Reports that Flandro's paper was based on to obtain an accurate picture and compare these documents with Flandro's later publications.

The conclusion that should be emphasized here is that Flandro's assignment of credit for the invention to Krafft Ehrichke on the basis of his 1962 *Space Flight* book is not supported by the evidence. The conclusive evidence can be obtained from Ehrichke's own words. In 1967, after he became aware of the invention and its significance, Ehrichke published a very long, 93 page paper that included an extensive survey of the development of interplanetary trajectory designs that included the invention of gravity-assist trajectories. (At that time, gravity-assist trajectories was also known as "swing-by trajectories," or "bi-planet trajectories"). Ehrichke assigned the primary credit to Walter Hollister and several other individuals that followed him. Quoting directly from page 176 in his 1967 paper, Ehrichke stated:

"In 1963/64 the final step was taken in the development of the bi-
planet mission analysis, namely to combine the perturbation maneu-
ver concept and the bi-planet capture mission concept (1963-4, 
1964-1, -2, -3, 1965-1, -3, 1966-1)."

The first reference that Ehrichke cited in this collection (1963-4), was Walter Hollister's 1963 Ph.D. Dissertation. Ehrichke identified his first paper in this field as a paper published in 1964. Since Krafft Ehrichke was one of the world's leading astrodynamists at that time, it is submitted that this 1967 publication by Ehrichke proves: (1) that gravity-assist trajectories was a radically new innovation that Ehrichke believed occurred in 1963; and (2) that Ehrichke obviously did not originate or describe it in his 1962 *Space Flight* book as claimed by Flandro.

For some reason not understood, Flandro is disregarding all of this documentation. In a recent interview conducted by James Oberg, a writer for *Astronomy* magazine, Flandro still claims that Ehrichke outlined the mechanics of gravity-assist trajectories in his book *Space Flight*. (See page 50, Ref. 129). He evidently described the invention to Oberg as comprising only one component.
(gravitational perturbations) instead of a combination of two (the other being multiplanetary trajectories) which were previously believed to be mutually exclusive prior to the invention. As a result, Flandro was able to convince Oberg that gravity-assist trajectories was an old idea used by Tsander in the 1920s. (The reader is encouraged to obtain a copy of this magazine article\textsuperscript{129} to understand how serious the problem is). As mentioned above, Flandro also describes the invention as represented by the other component (multiplanetary trajectories) thereby contending that the invention was still an old idea, but in this case, the inventor was Hohmann.\textsuperscript{128} Sometimes, Flandro claims that the invention was a new idea and claims that he was the person who invented it in 1965. (This will be described in detail later in this paper). One of the aims of this paper is to provide an accurate historical and technical description of the invention to writers and authors researching the history of space travel so that they will be able to give an accurate account of the invention.

**Documentary Evidence Showing That the Invention Was Not Expected or Predicted**

The documented evidence (i.e., the published historical literature) shows that since the inception of the possibility of interplanetary space travel by the early pioneers up to the time of the invention in 1961, every astrodynamist, propulsion engineer, and theorist who published technical papers addressing the problem of exploring most of the Solar System (i.e., the outer planets, regions close to the Sun and regions far above and below the ecliptic plane etc.) with instrumented spacecraft stated unequivocally that it could only be achieved by developing advanced propulsion systems such as nuclear/electric systems.\textsuperscript{46-80} And to show that there was no doubt about this belief, NASA spent almost two billion dollars trying. This is the irrefutable evidence that can be found in the technical aerospace journals from the 1950s and early 1960s that are still on the shelves in any large science/engineering library. The invention of gravity propelled space travel was the key that made it possible to explore the entire Solar System because those advanced propulsion systems were found to be beyond engineering feasibility.\textsuperscript{81-84} Thus, the invention was clearly not expected or anticipated. Rather, it was one of the most important in the history of science—the type that every young student of science dreams about.

The fact that the invention was new and unexpected can also be documented by examining the astrodynamics that was known regarding the two important components used in the invention before it became known, namely: (1)
the possibility of using gravitational perturbations to reduce the propulsion requirements for interplanetary space travel; and (2) the use of free-fall multiplanetary trajectories. It will be shown that before the invention became known, these two components were believed to be mutually exclusive. And, more importantly, each was shown to be completely impractical which we shall now document.

In 1959 the Idea of Utilizing Gravitational Perturbations to Reduce the Propulsion Requirements for Interplanetary Space Travel Was Proved to be Fundamentally Impractical

As pointed out above, by 1959, Lawden’s conceptual views on the possibility of utilizing gravitational perturbations to reduce the propulsion requirements for reaching another planet became identical with those of Tsander’s. The perturbing body was a moon orbiting the launch planet, or a moon orbiting the target planet. In several papers where Lawden mentions the theoretical possibility of utilizing such perturbations, he points out that a detailed quantitative mathematical investigation to determine the practical possibilities has never been carried out. (See page 181, Ref. 19). In 1959, Professor Samuel Herrick (who coined the term “astrodynamics”) decided to carry out the required investigation suggested by Lawden. The most promising application involved using the Earth’s Moon. However, Herrick’s analysis proved that the possibility was fundamentally impractical.\textsuperscript{150} He showed that the maximum 1.2 miles/sec. increase in velocity, with respect to the Earth, which could theoretically be obtained by passing close to the Moon via gravitational perturbations under ideal conditions, could be easily obtained with relatively little rocket propulsion close to Earth by simply extending the injection maneuver $\Delta V$ out of the parking orbit by only 0.1 miles/sec. Herrick pointed out that since this small additional velocity increment added to the injection maneuver near the Earth would probably be less than the required guidance propulsion approaching the Moon, the possibility was not only impractical, but it resulted in increasing the total propulsion requirements for interplanetary space travel instead of decreasing the propulsion requirements. Quoting directly from Herrick’s paper:\textsuperscript{150}

“"It was proposed that a rocket sent up close by the moon could be swung by the moon into an interplanetary orbit, with augmentation of its energy. In fact, the most that can be gained from the moon is twice its velocity of about 1.2 miles/sec. Unfortunately, the problem requires very careful maneuvering so that the moon will be passed at the exactly the right distance; otherwise the orbit will be bent too much or too little, and the rocket will be hurled in a direction far

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from its objective. The amount of fuel required for so delicate a maneuver would probably greatly exceed the fuel required for an additional burnout velocity of 0.1 mile/sec., which would give the projectile the additional velocity of 1.2 miles/sec at the moon's distance."

After Herrick published his analytical analysis showing that the idea of utilizing gravitational perturbations was fundamentally impractical, Lawden published a 130-page mathematical treatise on the optimal design of space trajectories in 1963, and made no mention of the possibility of utilizing gravitational perturbations for reducing the propulsion requirements for space travel.\textsuperscript{151}

It should also be pointed out that in view of Herrick’s 1959 paper,\textsuperscript{150} and Lawden’s 1960 and 1963 publications,\textsuperscript{44,151} the invention of gravity propelled space travel was clearly not a natural predictable evolution in interplanetary trajectory design. These papers, written by the world’s leading astrodynatists (and several others in the literature who could be cited), demonstrate that the opposite is true. Since the use of gravitational perturbations were shown to be impracticable, the invention was certainly not expected.

There is something else that should be mentioned which perhaps is the most conclusive evidence proving that the invention was not anticipated, expected, or predicted. The technical foundation upon which Minovitch’s invention rested was his discovery of a numerical solution of the Restricted Three-Body Problem of celestial mechanics for motion through the Solar System. In 1961, no one was even close to solving this problem.\textsuperscript{88} (The solution for an Earth–moon system was solved but not for the Sun-planet system because the distances were too great). Since this problem was not solved prior to Minovitch’s work, the idea of using the solution \textit{serially} to gravitationally catapult a free-fall spacecraft from one planet to another via orbital energy exchanges by Three-Body interactions was not likely to have been envisioned at that time.

\textbf{In 1962 a Numerical Solution of the Restricted Three-Body Problem for Interplanetary Trajectories Was Still Unsolved and Was Regarded as One of the Most Difficult Problems in Celestial Mechanics}

To fully understand the technical aspects of the invention, it is important to understand one of the most famous mathematical problems in history. The possibility of utilizing the gravitational influence of a planet such that its effect will accelerate a free-fall vehicle relative to the Sun and catapult it to another planet obviously requires the analytical ability to determine a precise approach trajectory to the perturbing planet such that its influence will, in fact, catapult the vehicle to the next planet. But since the vehicle moves under the simultaneous influ-
ence of the Sun and the perturbing planet, this "analytical ability" required—(in 1961) nothing less than a method for solving one of the most difficult unsolved mathematical problems in celestial mechanics—The Three-Body Problem. (The Restricted Three-Body Problem for interplanetary trajectories in three-dimensional space).

Newton's law of motion for two bodies moving under their mutual gravitational influence is represented mathematically by a second-order differential equation that is integrable to give closed-form solutions (i.e., conic sections expressed by quadratic functions). The position of each body at any future time can be determined by using these simple functions. However, if three bodies move under their mutual gravitational influence, the mathematical expression for determining their positions at any future time is represented by a system of second order differential equations, the general solution of which is unknown. This is the famous "Three-Body Problem" of celestial mechanics. The non-existence of closed-form solutions was proven by Poincaré near the end of the nineteenth century. The only way a solution could be obtained was via numerical integration/iteration techniques using the exact differential equations of motion starting from an initial approximation using a high-speed digital computer. Unfortunately, for interplanetary trajectories through the real Solar System, the initial approximation (of the approach trajectory) is so unstable, one has to be very close to the exact solution to obtain convergence (i.e., a precise approach trajectory defined by position and velocity vectors at a certain time that will send the vehicle to the target planet while moving under the continuous influence of the Sun, the encounter planet, and all of the other major bodies in the real Solar System acting simultaneously). At the beginning of the 1960s, this problem, represented by finding a method for calculating precise free-fall, round-trip, interplanetary trajectories such as Earth-Mars-Earth in the real Solar System, was far from being solved despite the considerable analytical and computational power used in the effort. Quoting directly from page 55 of Dr. Victor Szebehely's November 1962 paper on the determination of trajectories under the gravitational influence of more than one body, he stated:

"The field of orbit selection is closely related to orbit modification, its main problems being optimization and the establishment of the totality of possible orbits. Progress with the second avenue has taken place along two lines -- the mission -- oriented numerical computation of a large number of orbits and topologically oriented qualitative studies. It is interesting to note that the field of orbit selection, which is almost completely systems-engineering oriented, might benefit
greatly from the results obtained by the most sophisticated mathematical techniques.”

“This fact is not surprising when the standard systems-engineering question is recalled regarding the search for trajectories satisfying certain mission requirements. The desired trajectories—if they exist—can be computed by a digital machine, but their existence and their sensitivity to firing errors and delays are questions of higher order difficulty. Anyone who participated in establishing trajectories applicable to the basic or modified Apollo missions can testify regarding the difficulties involved. And is there anybody who did not participate? Round-trip interplanetary missions are on an even higher level of difficulty.”

Dr. Szebehely has written several books on the Three-Body Problem and was one of the most authoritative leaders in the field. The origin of “Chaos Theory” is directly connected to the instability of The Three-Body Problem.

After Minovitch completed his initial assignment to formulate a new method for numerically computing free-fall trajectories on a digital computer at JPL during the summer of 1961, he read Battin’s paper on the determination of free-fall round trip trajectories to Mars having the form Earth-Mars-Earth. Minovitch noticed that Battin treated the gravitational influence as an “instantaneous impulse” that occurred at the instant the vehicle crossed the orbit of Mars. He made no attempt to determine a precise three-dimensional passing trajectory which was required to actually achieve the round-trip trajectory without using any rocket propulsion. But this required a numerical solution to the Three-Body Problem. Since Minovitch was a graduate student in mathematics and not an engineer, he was able to recognize why the problem was so difficult. It was due to the complicated method for defining a conic orbit in three-dimensional space that was used in celestial mechanics at that time. It required the determination of six scalar “orbital elements” expressed as $a$, $e$, $i$, $\Omega$, $\omega$, and $T_p$. To make a long story shorter, Minovitch developed a new analytical approach based completely upon vector analysis. See pages 70-80 Ref. 1. This analysis replaced the classical scalar representation of three-dimensional conic trajectories with a vector representation using two orthogonal vectors $h$ and $e$, and methods for computing them from position vectors. By using this approach, Minovitch was able to determine a sufficiently accurate three-dimensional approach trajectory that would converge to the exact trajectory using standard integration/iteration methods for numerically solving the exact differential equations of motion corresponding to the real Solar System. However, at that time (July/August 1961) Minovitch did not know if the
method would actually produce a solution to the Restricted Three-Body Problem. But it did.

Minovitch started this work on his own initiative. It was not in any way related to his work assignment at JPL. This is an important historical fact. During this work, Minovitch noticed that the resulting planetary perturbations would have a strong effect on the orbital energy of the post encounter trajectory relative to the Sun. At that moment, the idea of a new method for achieving space travel throughout the Solar System without rocket propulsion became evident. All that was required was to apply the solution of the Three-Body Problem serially to a sequence of planets instead of only once. Thus, the first application of the solution would determine the precise approach trajectory to the first planet such that its influence would accelerate a free-fall vehicle relative to the Sun and catapult it to a second planet. The second application of the solution would determine the precise approach trajectory to the second planet such that its influence would catapult the vehicle to a third planet etc., that could, in principle, be continued indefinitely. No rocket propulsion is required except for a relatively little amount required to reach the first planet to get the process started and a bit more to deal with statistical trajectory errors. This is the technical background that is at the heart of the invention. It was a mathematical invention that would require a great deal of numerical investigation to determine if it had any practical possibilities. But it all hinged on the question of whether or not the vector methods really would solve the Three-Body Problem. The answer to this question was answered in April 1962. (See Ref. 101, and page 115 of Ref. 102). These methods later became his Ph.D. dissertation in mathematics at the University of California, Berkeley.  

Finally, to understand the significance of the invention, it should be noted that the concept of gravity propelled interplanetary space travel went deeper than a change in trajectory design. Since Herrick demonstrated that the idea of using gravitational perturbations to reduce the propulsion requirements for space travel was not practical, he essentially proved that reaction propulsion was the only viable means for propelling a vehicle through the Solar System. Therefore, Minovitch’s invention overthrew the most basic principle upon which the technical feasibility of interplanetary space travel rested—reaction propulsion.

Figure 12 is a reproduction of a hand written note from Mariner 2’s Project Engineer W. Eugene Bollman  asking Minovitch for the precise approach trajectory parameters for Mariner 2’s approach to Venus such that the gravitational field of Venus will bring the spacecraft back to Earth. At that time, Minovitch’s UCLA gravity propelled trajectory program was the only trajectory program at
JPL capable of determining these parameters (i.e., solving the corresponding Restricted Three-Body Problem).

Figure 12: Reproduction of a handwritten note from Mariner 2's Project Engineer W. Eugene Bollman asking Minovitch for the precise approach trajectory parameters for Mariner 2's approach to Venus such that the gravitational field of Venus will bring the spacecraft back to Earth. At that time, Minovitch's UCLA gravity propelled trajectory program was the only trajectory program at JPL capable of determining these parameters (i.e., solving the corresponding Restricted Three-Body Problem). (Courtesy of Michael Minovitch).
In 1962 Multiplanetary Trajectories Were Shown to Require so Much Launch Energy That They Were Described as “Academic Pastimes”

Prior to Minovitch’s invention, the idea behind a multiplanetary trajectory was the possibility of carrying out a reconnaissance of two different planets in one mission, using one vehicle. The trajectory design was based on finding a constant elliptical path with a period synchronized with the periods of the two planets such that the vehicle intercepted the orbits of the planets just as the planets were passing by. Since planetary perturbations destroyed the constant elliptical path, and hence the synchronization, they were regarded as annoying disturbances that had to be canceled out in order to achieve the desired planetary interceptions. The documented literature proves that this underlying trajectory design methodology was believed to be self-evident and was never questioned prior to Minovitch’s invention. Hofmann canceled out the perturbations by using on-board rocket propulsion. Crocco canceled them out by using the second intercepted planet (Venus) to cancel out the effect of the perturbations of the first planet (Mars). Regardless of which method was used to cancel out the perturbations, the resulting elliptical path had a high eccentricity which required very high launch energy.

In June 1962, Stanley Ross and his group of nine other leading astrodynami-
cists from Lockheed Sunnyvale, published an extensive 180-page “Final Report” on round-trip interplanetary trajectories for manned space travel.155 In Section 5 of their report dealing specifically with multiplanetary non-stop free-fall reconnaissance trajectories between Earth, Mars, and Venus, the authors describe the trajectories by stating:

“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 plants.”

This statement, written in 1962 by ten leading astrodynamists, is important because it described the minimum-energy requirements for achieving free-fall multiplanetary trajectories in terms of basic astrodynamical principles of multiplanetary space travel that appeared to be so obvious they were never ques-
tioned, and were believed to be unchangeable. It was shown that the departing trajectories had to leave Earth’s orbit at a fairly steep angle. The enormous launch energies resulting therefrom (the basic astrodynamics) were regarded as inherent in these trajectories. Thus, it was believed that these multiplanetary trajectories could only be achieved by brute-force rocket power, i.e., by developing nuclear propulsion systems. Since the required launch energies were so high, multiplanetary trajectories were considered to be completely impractical by leading astrodynamosicists. They were regarded as “academic pastimes.” This choice of words is significant because it indicates that these researchers regarded their analysis and conclusions as unchangeable mathematical certainties.

The Design of Multiplanetary Trajectories Taught by Leading Astrodynamosicists Before Minovitch’s Invention Became Known Was Based on Canceling Out the Effects of Planetary Gravitational Perturbations

As stated earlier, in 1962, Dr. Krafft Ehricke, published a 1,210 page book on the dynamics of space flight containing one of the most extensive investigations of multiplanetary free-fall trajectories ever made at that time.142 His underlying trajectory-design methodology was the same as Hohmann’s and Crocco’s. The design was based on finding an “ideal” constant unperturbed elliptical path leaving the Earth that would intercept the orbits of the target planets just as these planets were passing the intercept points. It was based on a “synchronization principle” that appeared at that time to be so intuitively obvious and self-evident in the design of multiplanetary trajectories that it was never questioned.156 Since the planetary gravitational perturbations tended to destroy this synchronism, they were regarded as a serious problem. Ehricke solved this problem the same way that Hohmann solved it—by using onboard rocket propulsion to cancel out the effects of planetary gravitational perturbations. Since this is such an important historical fact we shall repeat Ehricke’s own words (see page 1062, Ref. 142):

“Perturbations by the planetary encounter are assumed to be corrected, preferably while nearest to the planet so that a heliocentric ellipse closely resembling the original ellipse is resumed by the time the vehicle is sufficiently removed from the planet.”

These corrective rocket propulsion maneuvers to cancel out the effects of planetary perturbations required the expenditure of a considerable amount of rocket propulsion (which significantly increases if close passing distances are used to obtain good observations) even if the required launch velocities were low. But, as it was pointed out in the 1962 Lockheed Report,155 the launch velocities required to begin a multiplanetary trajectory connecting Earth, Mars, and
Venus were so high, it was believed that unless advanced nuclear propulsion systems were developed, the possibility of multiplanetary space travel could be regarded only as an "interesting academic pastime." These high-energy requirements only confirmed the previous results of Ruppe in 1959. Ruppe's 1959 work was important because it gave the "minimum-energy requirements" for multiplanetary and standard direct-transfer trajectories that were known since the early pioneers. Since these minimum-energy requirements were derived from the most firmly established principles of space travel based on several decades of research, the quantitative minimum-energies were regarded with mathematical certainty. For all practical purposes, they were regarded essentially as the basic launch energy requirements for exploring the Solar System with instrumented spacecraft and described as such in all the engineering handbooks on space travel. There was no expectation that anything would change. It was a mathematical certainty. Thus, the actual situation regarding the use of multiplanetary trajectories in June 1962 (the basic astrodynamical conclusions resulting from several independent studies) was:

1. the required launch velocities were so high they were considered to be way beyond the reach of chemical rocket propulsion and hence impractical; and

2. the effects of planetary gravitational perturbations had to be canceled out to achieve the planetary intercepts.

The key that linked the two mutually exclusive elements, free-fall multiplanetary trajectories and gravitational perturbations, was Minovitch's numerical solution to the Restricted Three-Body-Problem of celestial mechanics. After these components were joined mathematically in a synergistic relationship, the result was an entirely new theory of space travel. It is also important to recognize that before this link was achieved, both of these components were believed, and actually proved to be impractical, for exploring the Solar System. And, in 1962, a numerical solution to the Restricted Three-Body Problem for interplanetary trajectories was still believed to be a long way off.

The invention of gravity propelled interplanetary space travel changed the entire situation because it changed one of the most important and firmly established principles upon which space travel was based at that time—namely that reaction propulsion was the only practical means for propelling a vehicle through the Solar System. In 1961, 70 years after Tsiolkovsky laid the technical foundation for achieving interplanetary space travel that was confirmed by all the pioneers that followed him and the thousands that came after them, the possibility that a major portion of this foundation could be changed would have been regarded as preposterous by the professionals in 1961. But it was changed by the
invention of gravity propelled space travel that was made possible by solving the
Restricted Three-Body Problem of celestial mechanics. This was the link that
joined the two previously considered incompatible components, multiplanetary
trajectories and planetary perturbations, that were each considered to be imprac-
tical.

Examining the Evidence of Other Claimants

Since one of the aims of this paper is to demonstrate beyond any reason-
able doubt that gravity-assist trajectories was Minovitch’s invention, it is impor-
tant to understand the basic criterion that is used to determine the originality for
scientific discoveries. For all practical purposes this criterion is the rule of “first
disclosure.” The first person to write up a discovery in a documented paper hav-
ing a verifiable date is the person identified as “the discoverer” or “inventor.”
(This criterion is also used in American patent law). If a person believes he or she
made a new discovery, a paper describing the discovery with a date that can be
documented is essentially automatic and part of the discovery process. Every pro-
fessional investigator understands this. In most cases, the discoverer writes sev-
eral papers describing the discovery. It is part of the basic ground rules for sci-
entific research that are needed for establishing originality. Material without any
written description obviously cannot be accepted as documented evidence dis-
closing or describing an invention.

Since no documented paper by any claimant describing gravity-assist tra-
jectories can be produced that pre-dates Minovitch’s August 23, 1961 JPL paper,
Minovitch is the inventor. This can only be established by examining the evi-
dence put forward by the various claimants.

Stanley Ross

The first person to have published a paper claiming to have discovered
gravity-assist multiplanetary trajectories was Stanley Ross. The paper was dated
January 1963.\textsuperscript{157} (It was presented in two separate conferences\textsuperscript{158,159}). Ross dis-
closed a gravity-assist Earth-Venus-Mars-Earth trajectory that required a hyper-
bolic excess velocity (escape velocity) $V_e$ of only 3.78 km/sec. (See page 147,
Ref. 157). Ross gave the velocity (speed departing Earth) as 0.127 EMOS in
terms of a fraction of the Earth’s mean orbital speed which is 29.79 km/sec. Ross
explained the discovery as a trajectory predicted from Crocco’s Earth-Mars-
Venus-Earth multiplanetary trajectory using a “Reciprocity Principle” based on
the assumption of zero perturbations.

As pointed out above, Ross (and nine other leading astrodinamicists from
Lockheed) completed an extensive Final Report on interplanetary trajectories in
June 1962, and essentially proved that the required launch escape velocities $V_e$
of round-trip multiplanetary trajectories passing both of these planets and returning
to Earth were so high (about 12 km/sec) that they should only be regarded as
“academic pastimes.”155 Nothing was expected to change because it was believed
that these trajectories had to be designed close to constant elliptical paths with
periods synchronized with the periods of Mars and Venus in order to achieve the
planetary interceptions, and return the vehicle back to Earth. These conditions
required the trajectories to be fairly eccentric with very high launch energies. The
orbital periods had to be close to an integral multiple of the Earth’s period. These
were believed to be the basic self-evident astrodinamic conditions in the design
of these trajectories. (Ross’ Report was entitled: Final Report). Since planetary
perturbations destroyed the timing requirements, they were regarded as annoying
disturbances that had to be canceled out or corrected. By reversing Mars and Ve-
nus in the encounter sequence and using the gravitational field of Venus (a close
approach maneuver) to change the launch trajectory as in the trajectory disclosed
by Ross in his 1963 paper,157 —using a gravity propelled computer program to
compute the multiplanetary trajectories—the required launch energy ($V_e^2$) was
reduced to only 1/10 the previously believed minimum required values.24 And
this would make manned interplanetary missions to Mars possible with conven-
tional chemical rocket propulsion and Saturn V type launch vehicles.160 Thus, the
gravity-assist Earth-Venus-Mars-Earth trajectories represented a revolutionary
discovery in astrodinamics that would have profound implications for manned
missions to Mars. (They would become known later as “the Venus swing-by
mode”).

Ross’ paper also described gravity-assist trajectories with one fly-by of
Mars and two fly-bys of Venus having the form Earth-Venus-Mars-Venus-Earth.
(See page 148 of Ref. 157, and Ref. 161). This multiplanetary free-fall trajectory
involving three successive planetary passes with major trajectory changes in each
leg before returning to Earth without using any rocket propulsion after launch
was completely new and unheard of in astrodinamics. It was a major demonstra-
tion of what could be achieved with the concept of gravity-assist trajectory de-
sign using a very complicated gravity propelled trajectory program having the
capability of computing trajectories having four or more planetary encounters.
Unfortunately, Ross did not mention where he obtained this very complicated
trajectory program required to numerically compute these gravity-assist trajecto-
ries. An investigation in 1986 revealed that the trajectory program was Minovitch’s IBM 7090 gravity propulsion program that he designed and developed at UCLA to investigate his concept of gravity propelled space travel. Clarke made a duplicate copy of this program in June 1962 and sent it to Ross so that he could compute gravity-assist trajectories using Lockheed’s IBM 7090 computer. (See Ref. 146, page 8, Ref. 118, and pages 56-59, Ref. 2).

It is important to point out and emphasize that the first documented disclosure specifically mentioning the possibility of gravity-assist Earth-Venus-Mars-Earth trajectories was written by Victor Clarke on June 21, 1962. (See page 1, Ref. 96). This paper was a JPL RFP (Request for Programming) to JPL’s Computing Section (Section 314) to have Minovitch’s IBM 7090 computer program, that he wrote and developed at UCLA for computing gravity propelled multiplanetary trajectories, duplicated for JPL’s IBM 7090 computer. What Clarke did not tell Minovitch at that time was the fact that he sent a copy of the computer program to Stanley Ross so that Ross could compute gravity propelled multiplanetary trajectories on his IBM 7090 computer at Lockheed using the UCLA IBM 7090 computer program. This fact was to have enormous consequences on Minovitch’s career because, for reasons that are unknown, Clarke did not identify Minovitch as the inventor when he was passing out Minovitch’s UCLA gravity-assist trajectory program and informing others about the possibility of gravity-assist trajectories after Minovitch arrived at JPL in June 1962 to use the JPL computers. But there had to be someone to give the credit to in the professional publications.

**Walter Hollister**

The second person that claimed to have originated the idea of gravity-assist trajectories was Walter Hollister. Hollister named the idea “bi-elliptical transfers.” Hollister’s work was recognized as a new innovation by MIT’s Department of Aeronautics and Astronautics, and Hollister used it as his innovative requirement for his 1963 Ph.D. Dissertation at MIT. Quoting directly from page 7 in his dissertation:

> “Because of the large volume of work on different aspects of a mission to Mars it would be impossible to make reference to all of the literature on the subject. It should be noted, however, that the author has found no mention in the literature of the specific missions suggested in this work, namely trips to Mars via bi-elliptical transfer or via a Venus encounter that includes a significant velocity change near Venus.”
One specific bi-elliptical transfer (gravity-assist trajectory) that he singled out had the form Earth-Venus-Mars. This was the gravity-assist portion of the round-trip gravity-assist Earth-Venus-Mars-Earth trajectory that Hollister also mentioned in his Ph.D. Dissertation. (See pages 73, 77, Ref. 162). Hollister's 1963 Ph.D. dissertation is important because it establishes the fact that MIT's Department of Aeronautics and Astronautics recognized Hollister's claimed innovation. One of the prominent members of that Department was Dr. Richard H. Battin. The fact that Richard Battin also recognized Hollister's innovation is demonstrated by the fact that Hollister identified Battin as giving him assistance in computing his bi-elliptical transfer trajectories. (See pages iii, 71, Ref. 162).

In December 1965, Jack Lorell (one of JPL's finest astrodynamists) and Minovitch became aware of this dissertation for the first time during an AAS conference at UC Berkeley. It was cited at the conference as one of the originating publications describing a new trajectory design possibility that was to become known as "gravity-assist trajectories." Since Clarke had told Minovitch (and other JPL engineers) that he was informing Richard Battin and others about his gravity propelled trajectory research at UCLA and JPL, Lorell and Minovitch did not view the dissertation as original work (i.e., as a coincidence). Although Lorell believed that Minovitch should have protested the assignment of credit at the conference, Minovitch decided to take a plane back to Los Angeles and ask Clarke for help since he was responsible for making his work known to other researchers before he became recognized. Although Clarke admitted that he was responsible, his only response was: "I'm sorry but there is nothing I can do." This important history is documented in Minovitch's long letter to Professor Norriss Hetherington dated June 10, 197418 which he sent to over 20 JPL engineers (including Jack Lorell) and over 50 prominent scientists and NASA officials. (See Ref. 117, and pages 18 and 19, Ref. 118).

Robert Sohn

The next person that explicitly claimed to have originated the concept of gravity-assist trajectories in an AIAA "peer-reviewed" professional publication was Robert Sohn. Quoting from page 31 of this paper published in 1965163 Sohn states:

"An alternate mission mode suggested by the author as a general method for reducing Earth-entry velocities for all opportunities would be Venus swingby using the gravitational field of the planet to reduce Earth-entry velocity below 50,000 fps. The Venus swingby
mode is now receiving considerable study, and appears to have no basic limitations in navigation, launch delay, or other factors.”

What is interesting about Sohn’s claim is the fact that in 1964 he published a paper and cited Ross’ 1963 paper as preceding his own initial work on the concept, which it did.

During the latter 1960s, Hollister and Sohn were identified as the originators of gravity-assist trajectories (also known as ‘swing-by trajectories’) in the ‘peer-reviewed’ professional aerospace publications. For example, Ross described the innovation in a major 1965 publication (see page 3, Ref. 165) by stating:

“The labors of several of my colleagues and myself during the years of 1962 and 1963, and of the group at J.P.L. under Clarke during the same period resulted in the publication of a series of volumes comprising two planetary flight handbooks (1, 2), one devoted to the planning of manned flyby and landing flights to Mars and Venus, the other to unmanned probe missions to these same planets. Together, these handbooks blocked out and charted what we then considered to constitute all worthwhile mission areas for flights to the two nearest planets during the rest of this century. But the picture suddenly changed with the disclosures by Hollister (3) and by Sohn (4), in independent and almost simultaneous works, that the strong synodic fluctuation in mission requirements for fast round trips to Mars could be greatly reduced by employing close approaches to Venus enroute, causing its mass to modify nominally unacceptable trajectories to our favor (Fig. 1). Almost immediately, widespread attention was focused upon the ‘Venus swingby mission’ (as Sohn called it), and results of subsequent studies by Sohn himself and by Deewester were soon forthcoming.”

This explanation of the discovery was also ‘peer-reviewed’ and published in the Journal of Spacecraft & Rockets in a 1967 paper by Ross and Gillespie. Quoting directly from page 170 of their paper, the authors state:

“Hollister and Sohn, in independent and almost simultaneous works, demonstrated that the strong synodic fluctuation in mission requirements for fast round trips to Mars could be greatly reduced by employing close approaches to Venus enroute, causing its mass to favorably modify nominally unacceptable trajectories (Fig. 1). Almost immediately, widespread attention was focused upon the ‘Ve-
nus swingby mission” (as Sohn called it), and results of subsequent studies by Sohn\textsuperscript{3,4} and by Deerwester\textsuperscript{5} were soon disclosed.”

During this time, Minovitch was trying to publish the true story behind his 1961 discovery in prominent scientific journals such as *Science, Scientific American*, and in professional aerospace journals for almost a decade.\textsuperscript{167–175} (This was a very frustrating process and consumed an enormous amount of time). Since the editors of these publications required confirmation, they contacted JPL and talked to the only person that knew most of the early history, Victor Clarke, Jr. But Clarke, who was Minovitch’s 1961 JPL supervisor, refused to identify Minovitch as the inventor during that time. (This is what most young scientists fear the most in the beginning their professional careers). Since a former supervisor can always appear to be more believable than one of his part-time summer employees, all of Minovitch’s attempts to publish the true story of his invention of gravity-assist trajectories were rejected. However, Minovitch did have some important allies—the Director of JPL, Dr. William Pickering,\textsuperscript{112} and the head of JPL’s Systems Division (formerly Section 312), Elliott Cutting.\textsuperscript{111}

In 1966, Cutting made it possible for Minovitch to obtain JPL’s extended planetary ephemeris tapes that gave very accurate planetary position vectors for all the planets from 1950 to beyond the year 2000. Minovitch used these tapes to extend his UCLA planetary ephemeris (that ended in 1980) and numerically prove that his concept of gravity propelled space travel made it possible to explore the entire Solar System with only that amount of launch energy required for reaching Venus, the lowest amount required for reaching any planet. He conducted this research in the Mathematics Department at the University of California, Berkeley using a very fast CDC 6400 computer. He presented his results at the Proceedings of an AAS Symposium held in Boston May 25 -27, 1967. His paper was entitled “Gravity Thrust and Interplanetary Transportation Networks.”\textsuperscript{178} Figure 13 is a reproduction of Fig. 1 in this paper.

At the urging of Dr. Constantine Generales (one of the early pioneers of space medicine), whom he met at this meeting, Minovitch sent a copy of his paper to Dr. William Pickering with a personal letter.\textsuperscript{177} To Minovitch’s great surprise and delight, Dr. Pickering thanked Minovitch in a personal letter dated February 2, 1967.\textsuperscript{178} Dr. Pickering was the person who presented Minovitch with the first-place award for winning the 1963 AIAA Western Region Competition for original research, Ph.D category.\textsuperscript{179–182} (Also see pages 75–77 , Ref. 2). In 1970, Dr. Pickering published his very famous paper on gravity-assist trajectories giving the credit for the invention to Michael Minovitch.\textsuperscript{112} In October of the same year (1970) William Hollister published a paper on gravity-assist trajectories from MIT’s Department of Aeronautics and Astronautics (where he was an As-
sistant Professor and a colleague of Richard Battin) and gave the credit to Minovitch. But unknown to Minovitch, Pickering, Cutting, and JPL’s entire Systems Division, Victor Clarke (who transferred out of the Systems Division several years earlier) had already started claiming that he made the invention.

**Fig. 1 Earth - Venus - Earth - Jupiter**

**Figure 13:** Reproduction of Fig. 1 in Minovitch’s May 1967 AAS paper showing how it is possible to reach any point in the Solar System using only that amount of launch energy required for reaching Venus (which is the minimum required for reaching any planet). These are the type of very low launch energy gravity propelled trajectories used in the Galileo and Cassini missions. (Courtesy of Michael Minovitch).
Victor C. Clarke, Jr.

One of the most bizarre claims of having invented gravity-assist trajectories came from the same person who originally believed that it violated the law of conservation of energy in 1961, and refused to have it investigated at JPL—Minovitch's 1961 supervisor, Victor Clarke. In claiming the credit, Clarke described Minovitch as his "assistant." This information was sent to NASA and published as an official NASA News Release dated July 5, 1970. To explain the fact that Clarke never wrote any paper at JPL on gravity-assisted interplanetary trajectories prior to Minovitch's August 23, 1961 paper, he simply said that he hired Minovitch as his "assistant," presumably to work out the mathematics (i.e., solve the unsolved Three-Body Problem for interplanetary trajectories). Clarke never mentioned the fact that Minovitch had to conduct the research at UCLA because he refused to have it investigated at JPL. The overwhelming documentary evidence shows Clarke's story is not creditable. However, the fact that Clarke had some support at JPL is evident because the information in the NASA News Release was released at JPL, and sent to NASA Headquarters through official JPL channels where it was published as an official "NASA News Release." Quoting directly from this JPL/NASA News Release:

"The pioneer pathfinding trajectory studies of Victor C. Clarke, Jr., a senior JPL engineer, were recalled this week as he received a 1970 award from the Gravity Research Foundation of New Boston, N.H.

Clarke, mission analysis and engineering manager for the 1973 project, wrote a prize-winning essay on "The Application and Principle of Gravity-Assist Trajectories for Space Flight." He first demonstrated in 1961 the possibility of bouncing a spacecraft from planet to planet. ...

The use of a planet's gravitational field to change spacecraft speed and direction can significantly shorten flight times or make long missions feasible with present launch rockets. ...

Clarke, an engineer-scientist at JPL for 12 years, worked extensively in 1960 and 1961 on computing trajectories from Earth to Venus, Mars, Mercury and Jupiter. Jupiter is the pivotal planet for Grand Tour flights. ...

Theoretically, the process of diverting a spacecraft from one planet to another might be continued indefinitely, if the planets were in favorable positions," Clarke says. He recalled that his former assistant,
Michael A. Minovitch, then a UCLA graduate student, worked out an "eight-ball" gravity-assist trajectory, Earth-Venus-Mars-Earth-Mars-Earth-Venus-Earth, ...  
With the aid of UCLA and JPL computers, Minovitch worked out possible spacecraft trajectories for a decade of multi-planet missions, including Earth-Venus-Mercury in 1973.

These calculations all were prompted by Clarke’s 1961 study showing the feasibility of a simple Earth-to-Venus-and-return mission. ...

Clarke’s paper won fourth place in the Gravity Research Foundation’s essay contest. He received a 1969 NASA Exceptional Service Medal for his contribution to the Mariner Mars 1969 mission design."

JPL also informed the prestigious British Interplanetary Society that Clarke made the invention. The British Interplanetary Society published this claim on the most important invention in the history of space travel without any question.107 Quoting directly from page 88 in this publication, the author (P. J. Parker) states:

"NASA’s Jet Propulsion Laboratory is currently developing plans for two three-planet "Grand Tours" for the late 1970s. One mission would send spacecraft on a fly-by of Jupiter, Saturn and Pluto while the other would reconnoiter Jupiter, Uranus and Neptune. Both missions would use the application and principle of gravity-assisted trajectories for spaceflight as proposed by Victor C. Clarke Jr., (Senior JPL engineer and Mission analysis and Engineering Manager for the 1973 Mariner Venus-Mercury project) between 1960 and 1961. The huge mass and strong gravitational field of Jupiter (the pivotal planet for "Grand Tours") and the other larger planets make large deflections and speed changes possible for fly-by spacecraft, cutting journey times to Pluto to seven to eight years as compared to a 41 years direct flight."

Several facts should be noted. In June 1962, when Minovitch arrived at JPL to speed up his UCLA gravity propulsion research project by using the JPL computers, he did not become associated with Clarke, his trajectory group, or anyone else at JPL—and his use of the JPL computers was not under any JPL project. He used the computers on a stand-by, time-available basis as an extension of his UCLA research project. This was the agreement prior to his arrival in June 1962. He requested, and became attached to Dr. William Melbourne’s theo-
retical group. No one at JPL “directed” his research when he was using the JPL computers. What is so ironic about Clarke’s claim is the fact that Minovitch started the research project at UCLA because the idea of gravity propelled interplanetary space travel was rejected by Clarke as an impossibility in 1961 (see page 76, Ref. 91) and he refused to have it investigated at JPL at that time. Any explanation suggesting that Minovitch started the UCLA research project because he had “extra time to kill” and wanted to “learn computer programming” is not true. His academic work was confined to mathematics and theoretical physics. The last thing that Minovitch wanted to do was computer programming and data processing. Minovitch started the research at UCLA because his rough slide rule calculations indicated that the concept of gravity propelled space travel would work and that the most qualified research center that had the computer expertise to carry out the required numerical investigation refused to do it (i.e., Clarke refused to do it). Had Clarke indicated that he would carry out the investigation, Minovitch would have never interrupted his formal academic work and started the project at UCLA. JPL or NASA never provided any financial support for his research at UCLA and never supported the UCLA Computing Facility with any funding for any of the hundreds of hours that he used at the UCLA facility. (JPL did supply most of the computer paper. But this was trivial compared to the cost of using several hundred hours of computing time on UCLA’s IBM 7090 and 7094 computers). Most of the trajectory engineers in JPL’s Systems Analysis Section (Section 312) during the early 1960s knew this history, and the fact that Minovitch invented it and carried out the initial investigation. (See Refs. 1 and 2). There was never any question about who originated it among JPL’s engineering staff in Section 312.

As pointed out above, when Pickering was informed of Clarke’s claims, he conducted an investigation and determined it was Minovitch’s invention. Victor Clarke put this fact in writing in the form of a letter that he sent to Professor Noriss Hetherington dated July 22, 1974.119

Minovitch believes that the evidence Clarke presented to claim credit for gravity-assist trajectories and to claim that he worked on gravity-assist trajectories with Minovitch as his “assistant” was a statement he made in the Acknowledgment of his 1963 Technical Report where he mentioned Victor Clarke.144 The exact words from this Acknowledgment are as follows:

“The author wishes to express deep appreciation to the Computing Facility of University of California at Los Angeles for carrying out many of the calculations. If this facility or its operational policies did not exist, the numerical results describing these advanced interplanetary missions would have been greatly delayed. The program for the
IBM 7090 digital computer corresponding to the solution given in Part III was written at UCLA, whereupon the extensive calculations took place at UCLA and at the Jet Propulsion Laboratory. The author wishes to convey his gratitude to all the computer operators at both facilities for their kind and thoughtful assistance. The author also expresses his appreciation to Victor C. Clarke, Jr., of the Systems Analysis Section at the Jet Propulsion Laboratory, who was closely associated with the project and provided a great deal of valuable information aiding the numerical computations. The secretarial work of Miss Corinne Ward, also in the Systems Analysis Section at JPL, is also appreciated.

In order to understand this Acknowledgment statement, it is important to understand the history behind it. When Minovitch was granted unlimited computing time on UCLA's IBM 7090 computer on April 2, 1962, to greatly expand his numerical research, he needed vast amounts of computer paper that was not covered in the grant Minovitch was operating under to use the actual computer. The cost of this computer paper at that time was $10 per box. Since Minovitch was planning such a huge investigation, hundreds of boxes may be required. The cost of these boxes of paper was beyond Minovitch's personal finances. He called Victor Clarke on the phone to ascertain if he could arrange to have JPL supply this computer paper. Clarke indicated this could probably be arranged. Minovitch also asked Clarke if he could make it possible for him to use the JPL IBM 7090 computers late at night and during the weekends for computing gravity propelled trajectories when they were not being used for JPL or NASA projects. Clarke indicated that this could probably also be arranged. This is how Clarke "became closely associated" with Minovitch's UCLA research project. (See pages 54-46, 55-61, Ref. 2). The information that Clarke provided Minovitch involved the values of the physical constants that Minovitch was using to compute his gravity propelled trajectories. When Minovitch started his investigation at UCLA in January 1962, he needed the values of many physical constants of the Solar System such as the gravitational constants and radii of all the planets, the gravitational constant of the Sun, and the number of kilometers in one AU, etc. He initially obtained this information from UCLA's library and Department of Astronomy. When he arrived at JPL in June 1962 to use the JPL computers on a stand-by basis, he asked Clarke for the most accurate values of these constants. Clarke referred Minovitch to one of his JPL Technical Reports that gave this information. This was the total involvement that Clarke had with Minovitch's UCLA research project beyond informing Lockheed and MIT that these new tra-
jectories were discovered and being computed. (Ref. 146 and pages 8, 18, 19, Ref. 118).

In December 1974, Clarke attempted to get Minovitch to accept a joint monetary award from NASA worth several thousand dollars if Minovitch would agree to accept a story describing his 1962-1964 UCLA gravity propulsion research project as a joint effort conducted by Minovitch and Clarke.\textsuperscript{185,186} This was a complete shock to Minovitch because his UCLA research project involving hundreds of thousands of dollars worth of grants from the University of California (via IBM) was never funded by JPL or NASA. Minovitch rejected the proposal,\textsuperscript{187} informed the President of the California Institute of Technology, Dr. Harold Brown that the fraudulent proposal was made, and requested a formal investigation.\textsuperscript{188} (JPL is a research laboratory operated by the California Institute of Technology). Minovitch also informed JPL's Director, Dr. William Pickering.\textsuperscript{189} Dr. Brown's investigation confirmed the fact that Clarke’s proposal had no factual basis. This finding was made known to Clarke and his proposal was dismissed.\textsuperscript{190} Shortly thereafter, Clarke left JPL and terminated his employment at that Laboratory.

In view of the 1974 investigation at JPL by Dr. Pickering, and the 1975 investigation at Caltech by Dr. Harold Brown, the fact that the invention of gravity-assist trajectories was Minovitch's, and Minovitch's alone, was conclusively established. Unfortunately, JPL still refused to grant Minovitch "official credit" for his discovery (invention) that is granted to every person who makes an original discovery at Caltech. Although JPL published a book in 1989 and devoted an entire chapter to the invention of gravity-assist trajectories and identified Minovitch as the inventor,\textsuperscript{191} all subsequent efforts by Minovitch to obtain "official credit" from JPL by re-filing Gates' nomination of Minovitch for the invention that he submitted in 1971\textsuperscript{113} were simply ignored.\textsuperscript{192,202}

In a recent book entitled, \textit{Countdown: A History of Space Flight}, published in 1997 by T. A. Heppenheimer,\textsuperscript{105} the author correctly describes the invention as fundamentally important in the history of space travel because it made it possible to explore all the planets in the Solar System with instrumented spacecraft. This was not possible prior to the invention because of the extremely long trip times. (This was described by Lawden in his 1958 paper given in Ref. 19). Quoting directly from page 300 of Heppenheimer's 1997 book:\textsuperscript{105}

"While NASA-Langley was proceeding with Viking, JPL was seeking new worlds to conquer, and had found a new way to reach them. NASA by then was using the nation's most powerful rocket, the Titan III-Centaur. It had launched Viking and had the thrust to reach Jupiter as well as the outer planets. But these missions would take a
long time: sixteen years to Uranus, thirty to Neptune. In the words of Homer Stewart, the head of JPL's advanced-planning office, "The management problems in organizing and carrying out a direct 30-year mission to Neptune (sheer boredom on the part of the participants) look great enough to deter even the most determined explorer."

"The new approach relied on the fact that when a spacecraft flew past a planet, the planet's gravity, combined with its motion around the Sun, could deflect the probe in its trajectory and give it extra energy. When Mariner 4 had flown past Mars, for instance, it had picked up over three thousand feet per second in velocity. Jupiter could do even more, for it was the largest of the planets. It could add the boost of an extra rocket stage, entirely for free, and could reduce the flight time to Neptune to as little as eight years."

By writing, "JPL was seeking new worlds to conquer, and had found a new way to reach them," Heppenheimer was clearly giving the credit for the invention to JPL. Upon examining the acknowledgment page, we find that the information was provided by JPL. This suggests that since JPL is claiming credit for the innovation, and since JPL is refusing to give the "official credit" to Minovitch, then JPL is clearly planning to give the official credit to someone else. As far as Minovitch knows, JPL has never officially indicated to NASA that their News Release No. 70-112 of July 5, 1970 giving credit to Clarke for inventing gravity-assist trajectories was a mistake. Furthermore, in 1986 the NASA News Release was discovered on file in the National Air and Space Museum of the Smithsonian Institution and was being used for a proposed display in that very prestigious museum. (No museum in the world has ever explained how it became possible to circumvent the high-energy barriers of classical space travel based on reaction propulsion formulated by the early pioneers and explore the entire Solar System with conventional chemical rocket propulsion and small launch vehicles which was believed to be a physical impossibility in 1961-62).

**Gary Flandro**

Gary Flandro was the fifth person that claimed to have invented gravity-assist trajectories. In 1989, Robin Kerrod was writing one of the most detailed books ever written on the Voyager 2 mission. He was a prominent member of The British Interplanetary Society (a "Fellow") and author of many books on space travel. Kerrod wanted to know the origin of "gravity-assist trajectories" that was the basis for the Voyager 2 mission and consulted JPL. JPL directed
Kerrod to Flandro for an interview. During the interview with Kerrod, Flandro claimed credit for the invention by stating (see page 8, Ref. 207):

"My gravity-boost idea wasn’t new. Astronomers had known for a long time that a comet speeds up when it passes close to a planet. I was the first to apply the same idea to a spaceship."

Based on this information, the author gives a "Chronology" of the Voyager 2 mission on page 80 by stating:

"1965 Caltech graduate student Gary Flandro puts forward the idea of gravity-assist to reduce journey times to distant planets."

As in the case of all the other claims, this claim is not credible. The work that Flandro was referring to in the interview with Kerrod was actually assigned to him during the summer of 1965 by Elliot Cutting because Minovitch was not able to continue the work at that time.\(^{(147)}\) (See Figure 11). Thus, Flandro began his work four years after Minovitch wrote his 1961 JPL paper and over two years after he gave his technical seminars on the concept to JPL’s engineering staff.\(^{(208)}\) As described above, Flandro was given both of Minovitch’s JPL Technical Reports on gravity propelled trajectories where, on page 9 in the first Report,\(^{(144)}\) Minovitch explicitly claimed originality for proposing the concept that became known as gravity-assist trajectories by citing his 1961 JPL paper.\(^{(89)}\) The second Report\(^{(145)}\) contained the planetary configuration diagrams showing the relative positions of all the outer planets corresponding to various Earth-Jupiter launch periods from 1967 through 1978. These diagrams made it possible to identify all possible planetary encounter sequences involving all the outer planets by inspection without having to compute them. The third item that Cutting made available to Flandro was Minovitch’s gravity propelled computer program (equipped with an extended ephemeris) to numerically compute the encounter sequences identified from the configuration diagrams that Minovitch also constructed. Thus, in actuality, Flandro’s work during the summer of 1965 was “data processing” on a previously invented concept, using the concept and research tools that Minovitch invented and developed during the previous three years. Determining the numerical values of previously identified encounter sequences does not involve “discovering” or “inventing” anything. The Voyager 2 encounter sequence Earth-Jupiter-Saturn-Uranus-Neptune, and several other outer planet encounter sequences, were known and discussed at JPL during the summer of 1964 one year before Flandro was given his assignment. JPL lunar gravity pioneer William Sjogren commented on these interesting sequences in Minovitch’s office, an exchange confirmed by one of our authors (Ridenoure) in a 1993 discussion with Sjogren
at JPL. (See page 91, Ref. 2 and page 17 Ref. 118.) Minovitch originally identified these encounter sequences at UCLA during February 1962 prior to his numerical computations. (See page 5, Ref. 118, and pages 39, 40, Ref. 2.)

Richard H. Battin

The first paper that Richard Battin wrote describing an Earth-Venus-Mars-Earth gravity-assist trajectory was entitled, "The Trajectory Problem As It Relates To The Mission For Interplanetary Flight."209 This paper was part of a collection of papers published in a book entitled Air, Space, and Instruments, that was published in 1963. Battin claimed credit for discovering the first gravity-assist trajectory Earth-Venus-Mars-Earth in a 1994 paper by asserting that the manuscript of the book was delivered to the publisher (McGraw-Hill) in 1961 but the publisher delayed publishing the book for over one year. He offered no supporting evidence to confirm this assertion. Quoting directly from pages 5 and 6 of his 1994 paper,210 Battin states:

"A volume of original contributions titled Air, Space, and Instruments was planned to honor Charles Stark Draper on his sixtieth birthday which would occur on October 2, 1961. Hal Laning and I contributed a chapter 17 on our trajectory work for interplanetary missions. Unfortunately, the actual publication of the Draper Anniversary Book was delayed by the publisher and it did not appear until early in 1963... Needless to say, I was most anxious to publish the result. Our chapter for the Draper Anniversary Book was already underway and the multiple fly-by orbit would provide a really dramatic climax for our contribution. I would have published it in a separate paper had I known that McGraw-Hill would slip their publication schedule for the Draper volume by more than a year."

A careful reading of the various papers published in that book reveal that the manuscript could not have been submitted before May 16, 1962. On page 72 of that book a reference (50) was made, in the past tense, to a paper211 that was presented by the author (Herbert Weiss) at a Naval Research Conference during May 14-16, 1962.212 Quoting directly from this reference that was published in the Draper book:


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This provides conclusive evidence proving that the manuscript of the papers for the book was sent to the publisher by the editor (Sidney Lees) after this date. This is because the manuscript of the Draper book that contained Battin’s paper, as well as all the others, was sent to the publisher (McGraw-Hill) by the editor of that book (Sidney Lees) as one entire manuscript. It was not sent one paper at a time. The editor collects the papers, and delivers them to the publisher at the same time in the order that they will appear in the published book. Therefore, references to papers published in 1962 obviously mean that the manuscript for that book could not have been delivered to the publisher in 1961. (A copy of the paper that Weiss submitted at that conference is provided herein\(^{212}\)). There are other papers in the book citing other articles and books published in 1962. (For example, see Ref. 74, page 73, Ref. 4, page 96, and Refs. 4, 5, page 445). In addition, an investigation conducted by McGraw-Hill in 1997 indicated that the manuscript of the book was probably delivered between May and September 1962\(^{213,214}\). Therefore, Battin’s claim that the book containing his paper was sent to the publisher for publication in 1961 is not credible. Consequently, his 1963 paper\(^{269}\) can obviously not be used as documentary evidence for establishing a date for Battin’s claimed Earth-Venus-Mars-Earth gravity-assist trajectories predating Minovitch’s August 23, 1961 JPL paper.

The fact that Battin did not make the invention can be proved conclusively. In 1962, Battin acknowledged Walter Hollister as having made the invention. As described above, Hollister used his claimed innovation for satisfying the important innovative requirement for a Ph.D. dissertation in Battin’s Department of Aeronautics and Astronautics at MIT. The fact that Battin acknowledged Hollister’s claimed innovation can be established by the fact that he actually assisted Hollister compute his claimed bi-elliptical (gravity-assist) trajectories. Quoting directly from page iii, of Hollister’s Ph.D. Dissertation:\(^{162}\)

“The staff of the MIT Instrumentation Laboratory has been extremely helpful. Dr. Richard H. Battin, Dr. James S. Miller, Kenneth Fertig, and John L. Gropper have provided technical advice.”

This Ph.D. dissertation from MIT therefore represents conclusive proof that Battin did not make the invention because he recognized someone else. It should also be noted that numerous peer-reviewed papers were published in the professional aerospace journals during the 1960s giving credit for the invention of gravity-assist trajectories to Walter Hollister by citing this Ph.D. dissertation.\(^{163,166}\)

Additional evidence proving that Battin did not make the invention was provided by Hollister himself in 1970. In that year, Hollister (who had joined
Battin at MIT after he received his Ph.D. degree) published a paper on gravity-assist trajectories with Menning (from Lockheed Sunnyvale) and identified Minovitch as the inventor. Quoting directly from page 1193 of this paper:

“The use of a multiple swingby as part of an interplanetary mission was considered as early as 1925 by Hohmann and 1956 by Crocco. They each proposed interplanetary fly-by missions that would take a vehicle past both Mars and Venus before returning to Earth. Several investigators have subsequently studied this class of mission in more detail. It was Minovitch, however, who first recognized the fundamental role which the planetary flyby can play in trajectory design. He saw the planets as sources of free thrust which could be utilized to project a vehicle from one planet to another without the use of fuel. In Ref. 7 he described, for example, a round trip mission leaving and arriving Earth with six intermediate flybys at Venus, Mars, Earth, Mars, Earth, and Venus. He further proposed an interplanetary transportation network, using multiple fly-by trajectories that would continue indefinitely.”

The paper that Hollister cited in giving the credit to Minovitch was Minovitch’s August 23, 1961 JPL paper. The paper originated from Battin’s Department of Aeronautics and Astronautics. Clearly, Hollister would have identified Battin (his colleague and mentor at MIT) as the inventor in his 1970 paper if Battin’s alleged January 1961 discovery of gravity-assist Earth-Venus-Mars-Earth trajectories described in his 1994 paper were actually true. It is inconceivable that Battin would have kept this alleged discovery (which he describes as one of his most important discoveries) a secret from Hollister when Hollister claimed that he originated the concept in 1962 (which he named “bi-elliptical transfers”) and used for satisfying the strict innovative requirement for his Ph.D. dissertation at MIT which was approved by the Department of Aeronautics and Astronautics and acknowledged by Battin himself. It is therefore submitted that Hollister’s 1970 paper crediting Minovitch for inventing gravity-assist trajectories by citing his August 23, 1961 JPL paper also represents conclusive evidence proving that Battin did not discover or originate Earth-Venus-Mars-Earth gravity-assist trajectories prior to Minovitch’s August 23, 1961 JPL paper.

There is more evidence showing that Battin did not discover or originate gravity-assist trajectories in January 1961 as he claimed in his 1994 paper. In June 1962, 17 months after his claimed January 1961 discovery of Earth-Venus-Mars-Earth gravity-assist trajectories, Battin submitted a lengthy paper on navigation for round-trip free-fall trajectories to Mars and Venus. The paper in-
olved following the most suitable pre-determined round-trip trajectory (a reference trajectory) by the navigation system identified from previous investigations of round-trip trajectories. On the first page of this paper (page 1681) Battin described the round-trip trajectories that were investigated at MIT as the usual single-planet Earth-Mars-Earth and Earth-Venus-Earth trajectories, and explicitly made reference to them by citing previously published papers.216,217 The Earth-Mars-Earth trajectories required trip times of over three years. However, Battin's alleged Earth-Venus-Mars-Earth gravity-assist trajectories that he claimed to have discovered in January 1961 and "anxious to publish"210 represented a revolutionary discovery. These trajectories only required trip times of about 1.26 years, offered the truly remarkable and spectacular additional advantage of passing two different planets instead of one (accomplishing two missions for the price of one), and required approximately the same launch energy. (See page 118, Ref. 209). However, a close examination of his 1962 paper215 reveals that he made no mention of these revolutionary gravity-assist multiplanetary trajectories. Since it is unreasonable to assume that he did not mention these trajectories in his 1962 paper215 because he did not consider them important, this paper represents documentary evidence showing that when Battin submitted this paper for publication in June 1962 he was not aware of any gravity-assist Earth-Venus-Mars-Earth multiplanetary trajectories. It should also be noted that when Minovitch arrived at JPL to use their computers for his UCLA gravity propulsion research project in June 1962 and informed Clarke of his gravity-assist Earth-Venus-Mars-Earth trajectories, Clarke indicated that he would inform Stanley Ross at Lockheed and Battin at MIT. At that time the primary research group that NASA identified and awarded study contracts for investigating round-trip interplanetary trajectories to Mars and Venus was Stanley Ross' group at Lockheed Sunnyvale. Clarke believed that Minovitch's Earth-Venus-Mars-Earth gravity-assist trajectories should be made known to both of these individuals. Many engineers at JPL, such as Jack Lorell and Raoul Roth, were aware of the fact that Clarke was making Minovitch's gravity-assist trajectories known to other researchers when he arrived to use the JPL computers during the summer of 1962. (See pages 18, 19, Ref. 118, and Refs. 2 and 146). Minovitch started delivering his UCLA Earth-Venus-Mars-Earth gravity-assist trajectories28 to JPL by the truckload beginning May 4, 1962. (See Ref. 109, and Figs. 5 and 7). At that time, Minovitch was happy that Clarke was making his trajectories known to other researchers because that is why he was having his UCLA gravity propelled trajectory computations delivered to JPL and made available to anyone who wanted to see them.

There is another important fact regarding Battin's 1994 paper210 that should be mentioned. In the fall of 1990, one of our co-authors (William Kosmann) in-
terviewed Battin to determine when he first discovered gravity-assist Earth-Venus-Mars-Earth trajectories. During that interview Battin claimed that he discovered these trajectories during the 1959-1960 time period. When Kosmann asked for proof, he gave Kosmann copies of six lantern slides from MIT’s Instrumentation Laboratory dated May and August 1960. Figure 14 is a reproduction of one of these lantern slides. Since this information is important, Kosmann has submitted a notarized affidavit testifying under penalty of perjury that this is what Battin told him and gave to him as supporting evidence during that interview.218 (Copies of the six dated lantern slides that Battin gave him are attached to the affidavit as exhibits). According to this testimony,218 Battin never mentioned or showed him any dated computer printout or tabulator listing which played an important part in Battin’s 1994 paper.210 Minovitch wrote a letter to Kosmann for the historical record dated January 11, 1991 containing several documents proving that Battin’s claims were not credible.219,221

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**Figure 14:** Reproduction of one of six dated lantern slides from MIT’s Instrumentation Laboratory that Richard Battin gave to Kosmann during an investigative interview in the fall of 1990 as evidence to support his claim of discovering gravity-assist Earth-Venus-Mars-Earth trajectories during the 1959-1960 time period. (The date given on the slide is August 1960). (Courtesy of Michael Minovitch).
It should also be mentioned that the dated computer printout\textsuperscript{222} (tabulator listing) that Battin claims represents important evidence proving that he discovered and computed the first gravity-assist trajectory having the form Earth-Venus-Mars-Venus-Earth on January 26, 1961 using an IBM 650 computer\textsuperscript{210} has been examined and investigated by several forensic examiners and computer experts. The results of these investigations have been documented as formal reports and are historically significant in examining Battin’s claim to the invention. The results of the investigations found that the printout,\textsuperscript{222} and all other evidence and publications that Battin has presented to support his claim to the invention\textsuperscript{223-236} are false.\textsuperscript{237-235}

The fact that Battin could not have conceived or originated gravity-assist trajectories can be definitively established by the simple fact that in 1978 Battin published a paper on gravity-assist trajectories\textsuperscript{134} and gave the credit to Crocco by citing his 1956 multiplanetary trajectory Earth-Mars-Venus-Earth.\textsuperscript{132} Quoting directly from page 36 of Battin’s 1978 paper:\textsuperscript{134}

“One class of imaginative proposals for space missions exploited the gravity field of the planets to achieve multiple planetary fly-bys. Apparently, the first such study was presented in 1956 at the 7th International Astronautical Congress in Rome by the Italian G. A. Crocco.”

Since Crocco’s 1956 paper\textsuperscript{132} clearly shows that he regarded planetary gravitational perturbations as annoying disturbances that had to be canceled out to achieve his multiplanetary trajectory, Crocco’s trajectory was not a gravity-assist trajectory. Thus, Battin’s assignment of credit to Crocco was false. What is astonishing is that when Battin wrote his paper giving Crocco the credit,\textsuperscript{134} he knew that Crocco’s trajectory was not a gravity-assist trajectory because Mars was intercepted before Venus which he explained on page 185 in his 1964 book.\textsuperscript{256} Quoting from this page Battin wrote:

“The double reconnaissance mission designed at the end of Sec. 5.4 was originally suggested by Crocco (19). Unfortunately, the Crocco mission requires an excess hyperbolic velocity exceeding 38,000 fps owing principally to the fact that Mars was selected as the first planet to be visited. If the order is reversed and the gravitational field of Venus exploited, the mission can be accomplished with an excess velocity of only 15,000 fps.”

No matter how many papers that Battin publishes in his effort to claim the credit for originating gravity-assist trajectories, the fact that he published a paper in 1978 giving the credit to Crocco\textsuperscript{134} when he knew that Crocco’s trajectory was
not a gravity-assist trajectory proves that Battin did not originate gravity-assist trajectories. The only reasonable explanation is that Battin wanted to prevent the person who really originated gravity-assist trajectories from receiving the honor and recognition for this important invention—the invention that broke the high-energy barriers of classical space travel based on reaction propulsion that was believed to be unbreakable and, as a result, made it possible to explore the entire Solar System with instrumented spacecraft.

It is submitted that the documented evidence uncovered in the above investigation of the claims put forward by the various claimants shows that the person who originated the concept of gravity propelled interplanetary space travel, popularly known as gravity-assist trajectories, was Dr. Michael A. Minovitch. The fact that Dr. Krafft Ehricke (who was one of the most authoritative and leading astrodynamists in the world during the 1960s and 1970s) assigned the primary credit to Hollister in an exhaustive 1967 paper that included a detailed historical survey of the development of interplanetary trajectory design, the fact that Hollister identified Minovitch as the inventor in a paper published in 1970, and the fact that Victor Clarke, Jr. (Minovitch’s 1961 JPL supervisor) identified Minovitch as the inventor in his letter of July 22, 1974 removes all doubt.

**Summary**

After the rocket equation was derived in the 19th century by Tsiolkovsky, and after Hohmann discovered his cotangential “minimum-energy trajectory” in 1925, it became obvious to many early pioneers of space travel, that, in order to reach and explore most of the Solar System with space vehicles, new propulsion systems would have to be developed capable of generating very high exhaust velocities. In fact, one of the most famous pioneers, Hermann Oberth, proved that it would be physically impossible to reach and explore most of the Solar System with spacecraft. The energy densities and exhaust velocities of chemical propellants were far too low. Entirely new propulsion systems based on generating the propulsive energy by nuclear reactors and expelling the reaction mass at very high velocities by ultra high temperature nuclear-thermal or nuclear-electric systems were required. But the systems were all based on the principle of “reaction propulsion.” This was the basic technical foundation for the possibility of exploring the Solar System during the early 1960s when the effort to develop these advanced propulsion systems became very great, and on a world-wide scale. However, serious technical problems prevented their development, and it appeared
that most of the Solar System would remain out of reach and inaccessible for a very long time.

In 1961, Minovitch proposed a radically new method for achieving interplanetary space travel throughout the entire Solar System that required essentially no onboard rocket propulsion that could be initiated by a relatively small launch vehicle using conventional chemical rocket propulsion. It was based upon finding a numerical solution to the Restricted Three-Body Problem, and using the solution such that the gravitational influence of a passing nearby planet would catapult a free-fall vehicle to one or more other planets by repeating the process thereby achieving interplanetary space travel throughout the entire Solar System without rocket propulsion. Moreover, in view of the “equivalence principle” where gravitational mass is equal to inertial mass, the propulsive forces automatically increase in direct proportion to the mass of the spacecraft. Hence, after the spacecraft is launched, it will not matter how massive it is. No other propulsion system has this unique operating characteristic. To obtain an accurate technical understanding of the concept, it is important to emphasize that the numerical solution to the Restricted Three-Body Problem for motion through the Solar System was the crucial element because it enabled the approach trajectory at each planet to be precisely determined such that the gravitational influence would, in fact, catapult the spacecraft to the next planet. Thus, Minovitch’s invention of gravity propelled interplanetary space travel was not an engineering method of space travel, it was a mathematical method of space travel.

The theory is implemented by a very accurate system of Earth-based radio tracking antennas and a very accurate onboard guidance system. The numerical solutions are found using an Earth-based computer and the numerical data obtained from the tracking antennas. The solutions (of the required approach trajectory) that will enable the vehicle to intercept the next planet in a predetermined encounter sequence are transmitted and fed sequentially into the vehicle’s planetary approach guidance system prior to each encounter. Essentially no rocket propulsion is required.

Although the possibility of utilizing gravitational perturbations to reduce the propulsion requirements for traveling to another planet was recognized prior to Minovitch, this possibility was not recognized as having any significant effect in changing the minimum propulsion requirements. In fact, in 1959 Herrick proved that the concept envisioned at that time was fundamentally impractical. But Minovitch discovered (or invented) a new concept for utilizing gravitational perturbations using planets, and interplanetary detour trajectories to get to them, that was radically different from the previous concept using moons. Since his concept provided the key technical breakthrough that made it possible to explore
the entire Solar System, it is important to understand the basic features of his concept that clearly distinguish it from the prior concept.

When reaction propulsion was taken for granted as being the only possible method for propelling a vehicle through interplanetary space, the vehicle had to carry a large amount of reaction mass (propellant). The energy generating system required for expelling this mass at very high velocity also had to be carried by the vehicle. And the mass of these elements increased in direct proportion to vehicle mass. The invention of gravity propulsion changed the entire situation because it didn’t require any propellant, the propulsive forces increase automatically with vehicle mass, and the Solar System itself would provide essentially all of the propulsive energy required to explore it.

Finally, it should be noted that most scientific discoveries or technological breakthroughs involve a phenomenon in nature that has been previously observed and studied. However, if a researcher fails to recognize how the phenomenon can be used to create the scientific or technological breakthrough (i.e., if he or she fails to “discover it”) and regards the phenomenon as having little relevance to a basic problem, the person can obviously not be credited for discovering the breakthrough. This is a well-established tradition in scientific research. It is part of the established ground rules.

In the case of gravity propulsion, the underlying phenomenon is gravitational perturbations. Both Tsander (working in the 1920s) and Lawden (working in the 1950s) pointed out that gravitational perturbations could, in principle, be used to reduce the energy requirements for traveling to another planet. But the historical evidence clearly indicates that these researchers did not recognize how gravitational perturbations could be used to open the entire Solar System to exploration with relatively small launch vehicles and conventional chemical rocket propulsion. This was Minovitch’s discovery.

It should also be pointed out and emphasized that the early pioneers of space travel framed the possibility within an overall mathematical theory. This theory was based on reaction propulsion (described quantitatively by the “rocket equation”) and direct-transfer trajectories (described quantitatively to a close approximation by conic trajectories relative to the Sun) that were regarded as intuitively obvious and self-evident. Two of the most important consequences of this theory were: (1) the principle of “minimum-energy trajectories” known as “Hohmann trajectories” that gave the minimum energy requirements for sending a spacecraft to another planet (i.e., the minimum energy requirements for exploring the Solar System); and (2) the principle of “launch periods” that were periods of time lasting a few weeks when the energy requirements for launching a spacecraft to another planet were minimum. They were separated by much longer time
intervals equal to the synodic periods between the launch and target planets. These principles were among the most important principles of space travel because they laid the technical feasibility of exploring the Solar System with manned and unmanned instrumented spacecraft. By applying these principles to the planetary orbital elements of the actual Solar System, the precise minimum energy requirements for exploring the Solar System and the launch periods were determined quantitatively. Prior to Minovitch’s work in 1961, all of these numerical results (and the theory behind it) were universally accepted with mathematical certainty. The numerical results showed that a manned landing mission to Mars, and the exploration of most of the Solar System could not be achieved with chemical rocket propulsion. It could only be achieved by developing very advanced high specific-impulse propulsion systems. There was no expectation that anything would change because it was based on a well-established mathematical theory spanning several decades. Unfortunately, the required advanced propulsion systems were found to be beyond engineering feasibility. Thus, the manned exploration of Mars and the unmanned exploration of most of the Solar System with instrumented spacecraft could not be achieved within the theory of space travel laid down by the early pioneers. Minovitch’s theory of space travel overturned this classical theory and made it possible to explore the entire Solar System with conventional rocket propulsion. These are the historical facts that are provable directly from the documented literature.

In conclusion, it should be understood that since 1961, there have been two fundamentally different theories for propelling a space vehicle through the Solar System. One theory, reaction propulsion, proposed and formulated by Tsiolkovsky, Goddard, and Oberth (based on an “engineering method” using a great deal of hardware and propellant that Goddard helped to develop) which could not generate the high velocities required for exploring most of the Solar System——and Minovitch’s theory proposed and formulated in 1961 (based on a “mathematical method” that he invented by solving a famous mathematical problem called the “Restricted Three-Body Problem”) that did enable the entire Solar System to be explored.

This is what his invention represented and accomplished and why it is fundamentally important in the history of space travel. It literally opened up the entire Solar System for exploration with instrumented spacecraft and it was achieved with relatively small launch vehicles and little conventional chemical rocket propulsion, and essentially no subsequent reaction propulsion. Thus, it achieved what was believed to be a physical impossibility in 1961. Very few innovations in the history of science have made it possible to break through a fundamental energy barrier, believed to be technically impossible to penetrate, and
obtain so much new scientific information for mankind in such a short time. Minovitch achieved this by creating an entirely new theory of interplanetary space travel—gravity propulsion. And this made it possible to determine the structure of the entire Solar System with instrumented spacecraft.

In 1991, Dr. Michael A. Minovitch was officially nominated for the 1992 Nobel Prize in physics for opening the entire Solar System to exploration with instrumented spacecraft by his invention of gravity propelled interplanetary space travel and solving the famous unsolved Restricted Three-Body Problem in analytical mechanics that made it possible.257

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Letter from Minovitch to Kosmann, January 11, 1991 (This letter was eight pages long and provided overwhelming documentary evidence proving that Battin’s claim was not credible).

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221 Reproduction of Battin's alleged lantern slides that are identified with handwritten numbers 18831-18836 showing drawings of gravity-assist Earth-Venus-Mars-Earth trajectories that Battin claims were made at MIT's Instrumentation Laboratory on February 7, 1961.


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