The shorter two-planet flight required spacecraft designed for only a 4-year mission—not 12. The *Mariner Jupiter-Saturn* project would use a gravitational assist at Jupiter to reach Saturn, but the Grand Tour mission to encompass four planets was dead.

DISCOVERY OF THE GRAND TOUR *VOYAGER* MISSION PROFILE

by Dr. Gary A. Flandro

PART 1

The work that led directly to the Grand Tour began at the Jet Propulsion Laboratory in 1965 when I was given a summer position to supplement my Ph.D. stipend as a graduate student in aeronautics at the California Institute of Technology. I had worked at JPL several times previously doing engineering work on missile trajectories, aerodynamics, and guidance systems. I learned as much from working there as from any of my formal graduate studies. The outstanding engineers at JPL had been a major inspiration for me to pursue graduate studies in space science.

Gary A. Flandro
Courtesy of Gary A. Flandro

My supervisor was Elliot "Joe" Cutting, with whom I had worked earlier on some trajectory problems. Joe assigned me the task of identifying possible unmanned missions to the outer planets. That was quite a leap at a time when America's longest spaceflight had been *Mariner 4* to Mars. The mere thought of missions to Saturn and beyond caused spacecraft engineers to tremble. The great distances to those bodies required long flight times. In 1965 the problem of building reliable mechanical and electronic devices with lifetimes long enough for trips to Mars (about 9 months) had not been truly solved. Missions that required vehicles to perform flawlessly for 9 years or longer were thought to be beyond our technical capability. Flights to Jupiter would take about 2 years, possibly just within our grasp, but missions to Neptune or Pluto would require approximately 40 years with the minimum energy transfer trajectories used in most space exploration. Another very worrisome problem was the difficulty of communicating over such vast distances. In light of these and other practical considerations, NASA and JPL management had little interest in outer-planet exploration in 1965.

It was a great challenge to try to make exploration of the outer planets practical. I examined the conventional spaceflight trajectories to reach an outer planet with the least energy expended, in which a spacecraft is treated as a miniature planet in an elliptical orbit around the Sun. The vehicle's perihelion is the Earth's orbit, its aphelion is the target planet's orbit, and the flight is timed so that the spacecraft will arrive at the target planet's orbit just as the planet itself reaches that position. For trips beyond Jupiter, the flights took too long. We needed more speed, but we could accelerate the payload in a major way only during the rocket burn following launch. After that, a spacecraft bound for the outer planets constantly loses speed because of the Sun's gravity. To get more launch energy required either larger and more expensive rockets or much smaller and lighter space vehicles. Practical limits in both those directions had apparently already been reached. Was there some other energy source that could be tapped en route to increase the speed of the spacecraft? That was the key realization.

Astronomers had known since the late 1600s that when a comet passes close to a massive planet like Jupiter, its kinetic energy is changed tremendously and its orbit is greatly perturbed. Spaceflight pioneers understood this but did not realize its potential. The earliest study of "indirect" trajectories that used intermediate planets to mold the flight path in a desirable way was by Walter Hohmann in his book *Die Erreichbarkeit der Himmelskorper* (The Accessibility of the Celestial Bodies), published in 1925. He called these multiplanet trajectories the "Hohmann route" and designed the first Earth-Mars-Venus-Mercury flight paths.

In this work also, he first described the Hohmann minimum energy transfer orbit—the cost-effective trajectory utilized by a majority of planetary space missions.

Much later, indirect trajectories were proposed by Gaetano Arturo Crocco, the Italian scientist and aviation pioneer. He discovered that flight paths between the Earth, Mars, and Venus could be designed to utilize energy losses and gains in repeated close flybys to keep a space vehicle continuously in what he called the Grand Tour of the inner solar system. Crocco described his discovery in 1956 to the Seventh International Astronautical Congress in Rome.

The space age began the next year, but scant attention was paid at first to such trajectories in the technical literature on spaceflight. An exception was Krafft Ehricke, one of the original Peenemunde scientists. In *Space Flight* (1962), his voluminous work on applied celestial mechanics, he described the physical situation most clearly: "One rule, however, remains generally valid: *If at all possible, maneuvers for changing the heliocentric orbital elements should be carried out during the hyperbolic encounter with a planet, rather than in heliocentric space.* The greater the planet's mass, the greater the energy saving." But attention in the early 1960s was focused on the completion of simple one-target missions, so multiplanet flight paths did not attract much attention.

By 1965, however, JPL investigators were examining gravity-assist flight paths. Joe Cutting and Francis Sturms had devised a trajectory to the innermost planet Mercury that used a flyby at Venus to drop the spacecraft in toward the Sun. This concept became *Mariner 10,* the first successful multiplanet mission, and returned fantastic pictures of Mercury's surface.

Also working on gravity-assist possibilities that summer at JPL was Michael Minovich, a UCLA graduate student in astronomy, but our paths seldom crossed because he preferred to work at night. He was studying trajectories that used close flybys of Jupiter for the purpose of either escaping the solar system or making close approaches to the Sun. If a spacecraft caught up with a planet from behind, it gained energy and was flung outward at an increased speed instead of returning to the inner solar system on its original elliptical trajectory. If a spacecraft crossed in front of a planet, it lost energy and fell in closer to the Sun. Joe Cutting suggested that I examine gravity assist as a means for reaching the outer planets.

Strange as it now seems, many JPL engineers had misconceptions about gravity assist in 1965. They knew that because of gravity a spacecraft would gain speed as it approached a planet and lose speed as it coasted away, but they thought that there would be no net change in the spacecraft's energy relative to the Sun. They failed to consider that the planet was in motion around the Sun and could itself lose energy as it accelerated the spacecraft.

Another misconception was that multiplanet trajectories took a spacecraft out of the most direct orbital course to its final target and that therefore a gravity assist would *increase* rather than *decrease* flight time. This was a natural conclusion reached from examination of Hohmann's calculations and early multiplanet concepts such as those used in

Mariner 10. For *Mariner 10* to travel from the Earth inward toward the Sun required that kinetic energy be *reduced*. The net result was that flight time to Mercury via Venus was longer than a direct elliptical transfer would require.

The work of Minovich on solar system escape trajectories demonstrated that these were truly misconceptions. It became clear to me that the key to the outer solar system was to utilize the gravity-assist method. It was also obvious that Jupiter, with its enormous mass to bend spacecraft trajectories, was the best energy supply station, since its distance was reasonable, requiring typically a two-year flight time.

With these considerations in mind, I began detailed studies of Earth-Jupiter-Saturn trajectories. Previous work of this sort had been elementary, aimed just at establishing the feasibility of such orbits. My task was to calculate realistic mission profiles so that estimates of actual flight times, payloads, and planetary approach distances and speeds could be made. Of greatest importance was to identify "launch windows," periods during which such missions could be initiated.

In July 1965, I found that the best launch dates for a Jupiter-Saturn trajectory occurred in the late 1970s, perfect timing for the developing space-exploration program. I located the optimum launch dates by drawing graphs of the planetary longitudes for all of the outer planets.

It was at this time that I discovered something that had apparently not been noticed earlier: In the early 1980s, all of the outer planets would be on the same side of the Sun and in amazingly close proximity. This conjunction of the outer planets provided the inspiration for the Grand Tour mission concept. I could see immediately that a single spacecraft could explore all four giant outer planets by using each planet in succession to modify the spacecraft's trajectory as necessary to rendezvous with the next planet in the series.

PART 2

This was a rare moment of great exhilaration. Instantly it was mixed with a considerable amount of skepticism; I found myself doubting that anything practical could be done with the Grand Tour in view of our nation's slow progress in attaining spaceflight capability. However, ten years were available to overcome the engineering difficulties, and on second thought, motivation supplied by a goal like this one could have a real impact on progress.

I immediately began work to determine if practical multi-outer planet trajectories could be located. The trajectory computer programs available were not truly adequate for the job. I evolved a hand method using tabulations and graphs for "matching" the trajectories across each planetary encounter. Later, conic trajectory programs were developed that automated this tedious process. I set up a sequence of about ten trajectory runs each night and submitted these to the programmer (it was a job-shop computer operation in those days) and picked up the results the next morning. I would then examine these results to determine the next set of runs.

It took about a thousand trajectories to map out the original mission profiles and launch dates for the Grand Tour. These were plotted on graphs showing launch dates versus arrival dates, with spacecraft launch energy as the variable. This made it easy to visualize when and how the best mission possibilities would occur. The best launch window was in September 1978, with acceptable windows in 1977 and 1979. The actual launch dates used in the *Voyager* missions were virtually the same as those worked out by primitive methods in 1965.

Convincing others that the Grand Tour constituted a real mission opportunity was the most difficult part of the job. Cutting saw the possibilities immediately, but there were many naysayers in the ranks at JPL. They scoffed at designing a space vehicle that could survive many years and a close passage at Jupiter.

Eventually I was asked to present the Grand Tour concept to Homer Joe Stewart, one of my professors at Caltech, who also worked at JPL as director of the advanced concepts group. He saw the potential instantly.

The very next day, JPL issued a press release describing the Grand Tour to the outer planets. Serious consideration of a multi–outer planet mission at JPL had begun. It eventually culminated in the successful *Pioneer 11* and *Voyager 1* and *2* missions.

Public opposition to the Grand Tour appeared at once. A hippie group, upon reading in the press release that the energy for flinging the spacecraft outward came at the expense of Jupiter's orbital energy, decided to organize the Pasadena Society for the Preservation of Jupiter's Orbit. They paraded in downtown Pasadena carrying signs, one of them wearing a flowing black cape and top hat, and held meetings for a short time in a good-natured way. But the real problems for the mission came later.

PART 3

The summer was over. My direct involvement with Grand Tour planning was finished, although for several years I continued to aid in the marketing of the mission concept by presenting technical papers and answering questions from the press. There was widespread acceptance of the idea with such notables as Wernher von Braun and President Nixon indicating support. In 1972, I received the annual Golovine Award of the British Interplanetary Society in recognition of my work in celestial mechanics. I had been nominated for this award by William H. Pickering, the JPL director.[1]

In the meantime, things had not gone well for the Grand Tour mission. The original very ambitious JPL plan involved a spacecraft that would have ejected atmospheric probes and orbiters at each intermediate planet. That mission was canceled in 1971 because of NASA budget restraints, but then a less ambitious *Mariner*-class spacecraft design was substituted. This "plain vanilla" plan was still based on the original Earth-Jupiter-Saturn gravity-assist flight path.

When it became apparent that the outer-planet Grand Tour mission would indeed fly, several individuals came forth claiming to be the originators of the idea. Truly, the multi–outer planet mission concept is the outcome of the work of many people. Walter Hohmann, originator of the multiplanet trajectory, and G. A. Crocco deserve as much credit as anyone for suggesting the use of gravity assist in planetary mission design and for the name Grand Tour. The solar system escape and close solar probe study by Mike Minovich demonstrated the benefit of the Jupiter gravity-assist maneuver.

The two *Voyager* spacecraft proved so reliable in the first legs of their flights that the *Voyager 2* flight plan was extended to perform the full four-planet Grand Tour mission, which will culminate when *Voyager 2* makes its final encounter, at Neptune, in August 1989, 24 years after my memorable summer at JPL.

[1]William Hayward Pickering (b. 1910) is no relation to William Henry Pickering (1858–1938), predictor of trans-Neptunian planets.

Resurrection

Almost, but not quite. NASA began plans for a third *Mariner* probe to be launched on a Jupiter-Uranus mission in 1979. In 1975, the Jupiter-Uranus project and the third spacecraft were canceled for lack of funds.

In 1977, the *Mariner Jupiter-Saturn* project was given a more manageable name—*Voyager*. And the *Voyager* management team took a final fond look at the Grand Tour plan. The highest priority objectives at Jupiter and Saturn included not just data from the planets but also close-up pictures and measurements of Jupiter's innermost large moon, Io, and Saturn's largest moon, Titan.

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Planets Beyond

Discovering the Outer Solar System

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