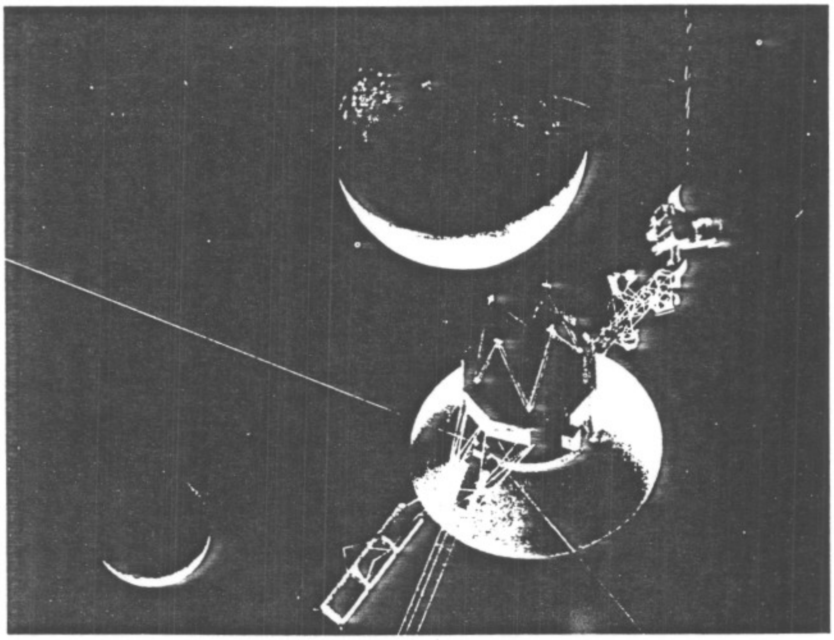
From
M. Chahine

JPL Publication 89-24

The Voyager Neptune Travel Guide



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NASA
National Aeronautics and
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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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> ***Any sufficiently advanced technology is indistinguishable from magic.***
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> *Arthur C. Clarke*

7. *SLINGSHOT MAGIC*

You decided long ago that you wanted to go on a Grand Tour of exploration, and your destinations were clearly defined. Your ship is equipped with the latest in scientific instruments, onboard computers, and communications gear. The main problem is that your speed leaving Earth is not fast enough (considering the Sun's gravity) to carry you much beyond Jupiter—the first of your four destinations. To accomplish the trip, you must find a way to increase your speed relative to the Sun.

A nice fusion drive would do the trick—or maybe a matter/anti-matter engine—but these new technologies just aren't around yet. Fortunately, by selecting the proper flight path by each of your destinations, you will be able to "steal" some precious speed, fly on to the next more remote destination, steal some more speed, and complete your Grand Tour. Knowledge has saved the day, and your clever scheme will be called "gravity assist."

A Change in Attitude

The techniques used in the design of planetary missions really did not change all that much from the 1920s to about 1960. In the 1920s, Walter Hohmann discovered the lowest energy (least departure speed) path between any two planets. As shown in Figure 7-1, that path is an ellipse that is tangent to the orbits of both the departure planet and the destination planet.

Planetary mission design primarily consisted of determining the launch times for Hohmann transfer ellipses from Earth to the various planets. With the rockets that existed by the 1950s, it was thought that it would be a very long time before people could send spacecraft beyond the planet Jupiter. The energies required for even the "minimum energy" Hohmann ellipses to the outer planets were far in excess of what chemical rockets could deliver at that time.

Further complicating matters were the long travel times the Hohmann ellipses required. For example, an Earth-to-Pluto Hohmann ellipse required a 40- to 50-year one-way travel time. An Earth-to-Neptune Hohmann ellipse required a 30-year travel time. It seemed as though not many planets would be visited in our lifetimes.

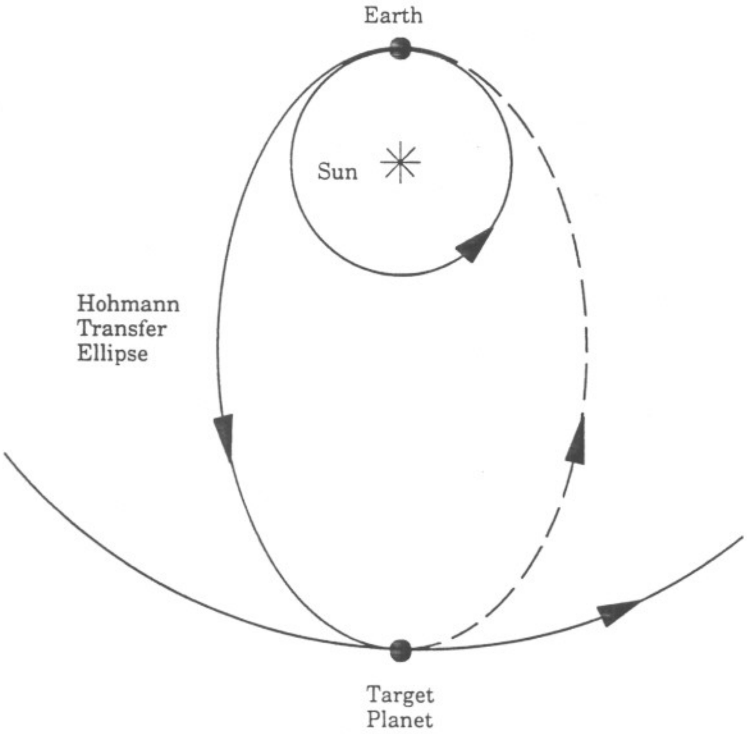
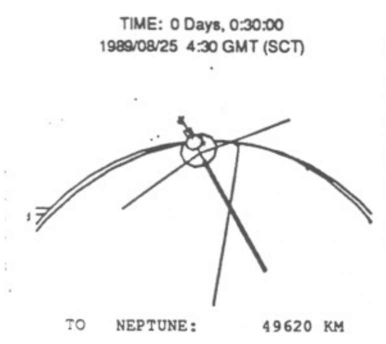


Figure 7-1. A Hohmann transfer ellipse, tangent to the orbits of both the planet one is leaving and the planet one is going to, requires the least departure energy or speed.

In the summer of 1961, a 25-year-old graduate student in mathematics, hired as a summer employee at JPL, created a revolution in planetary mission design. Michael A. Minovitch showed how to gain extra speed by properly selecting the path from planet to planet.

Minovitch wondered if the gravity field of a planet could be used to provide thrust to a spacecraft. Many others before him had thought about the effect of planetary gravity fields on passing bodies. But, by 1960, most planetary mission designers considered the gravity field of a target planet to be somewhat of a nuisance, something to be cancelled out, usually by onboard rocket thrust.



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. Such a boost could be obtained from the second planet to go on to a third planet, etc. The only energy required would be the launch from Earth to the first planet. All subsequent planets were

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By 1962, Minovitch had realized that using the gravity field of Jupiter was the key to outer planet exploration. Jupiter is the largest planet and, as such, possesses the strongest gravity field. Jupiter could be used to quickly slingshot spacecraft to Saturn, Uranus, Neptune, and Pluto, making such missions possible for the first time. That same summer, Minovitch realized that launch opportunities to the outer planets, via Jupiter, were possible from 1962 to 1966 and then recommenced in 1976 until at least 1980. He graphically illustrated the trajectory of an Earth-Jupiter-Saturn-Neptune Grand Tour, using a 1976 launch.

In 1964, Maxwell Hunter publicized Minovitch's gravity-assist concept in an outer planets mission design paper. The next year, Gary Flandro (then at JPL, presently founder and president of Wasatch Research, Inc.) designed a set of Grand Tour trajectories using the gravity-assist concept, including an example of an Earth-Jupiter-Saturn-Uranus-Neptune mission. He pointed out that these planets align themselves for this mission only once every approximately 176 years. The next set of Earth-launch opportunities would occur in 1976, 1977, and 1978. This provided the impetus for what ultimately became the Voyager Project, including Voyager 2's Grand Tour of the outer planets.

Real Applications

The first application of the gravity-assist concept for planetary exploration occurred in Mariner 10's Venus/Mercury mission. The Mariner 10 spacecraft was launched from Earth in 1973 and travelled directly to Venus via a Hohmann transfer ellipse, using the gravity-assist technique at Venus in February 1974 to get a boost on to Mercury. At Mercury in March/April 1974, Mariner 10 received a second gravity assist, which allowed the spacecraft to encounter Mercury a second time, in September 1974. A third gravity assist was performed at the second Mercury encounter to enable a third and final Mercury encounter in March 1975.

The second application of the gravity-assist concept occurred as a part of the Pioneer 11 mission. This spacecraft was originally intended to encounter only Jupiter (in 1974), as a precursor to the Voyager-1 and -2 encounters. However, the opportunity existed to execute a gravity assist at Jupiter to go on to Saturn, and Pioneer 11 was able to take advantage of this opportunity. Pioneer's gravity-assisted turn was almost 180 degrees, causing the spacecraft to travel all the way back across the inner solar system to pass closely by Saturn five years later, in 1979.

Meanwhile, at JPL from 1974 to 1976, Paul Penzo, Andrey Sergeyevsky, Joseph Beerer, and Charles Kohlhase evaluated the merits of over ten thousand different Voyager trajectories. The objective of the study was to maximize the total amount of knowledge that could be gathered from the Jovian and Saturnian systems. Of primary interest were Jupiter's moon Io and Saturn's moon Titan. Each pair of Voyager 1 and 2 trajectories had to have at least one close approach to each of these two moons. Additionally, the best trajectories had the largest number of close flybys of the remaining Jovian and Saturnian satellites. The final trajectories flown are shown in Figure 1-4, and include two gravity swingbys at Jupiter, two at Saturn, one at Uranus, and one at Neptune.

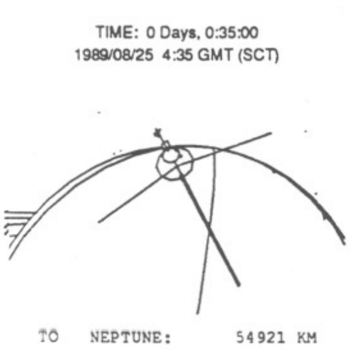
Gaining Speed Along the Way

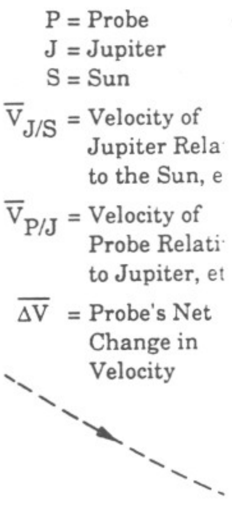
Gravity assist is created by causing a spacecraft to pass by a planet in a carefully controlled manner, as shown in Figure 7-2. A spacecraft may pass by the trailing (or leading) hemisphere of a planet. The close passage causes two things to occur. First, the spacecraft's path is bent. Second, the spacecraft either gains or loses energy (speed), as described below.

The bending occurs regardless of whether the spacecraft passes by the leading or the trailing hemisphere. The direction of the bending is selected by picking the proper hemisphere. The amount of bending is controlled by picking the closest approach distance to the planet. The bending in the flight path occurs both with respect to the planet and with respect to the Sun.

There is no *net change* in speed, however, *with respect to the planet*. The spacecraft is in continual free-fall with respect to the planet. Its final speed (far after approach) is exactly the same as its initial speed (far before approach) *with respect to the planet.*

With respect to the Sun, the story is quite different. First note that the spacecraft's velocity relative to the Sun is always equal to the spacecraft's velocity relative to the assisting planet *plus* (vector addition) that planet's velocity relative to the Sun. *From the point of view of the Sun*, when comparing the pre- and post-swingby spacecraft velocities, Figure 7-2 shows that this results in a net increase in the speed of an outbound (i.e., going away from the Sun) spacecraft (and, not shown in the figure, in a net slowing down of the planet). Energy has been transferred from the planet to the spacecraft. On the other hand, if an outbound spacecraft passes by the leading edge of the planet, from the point of view of the Sun, the roles are reversed: the spacecraft slows down and the planet speeds up. In





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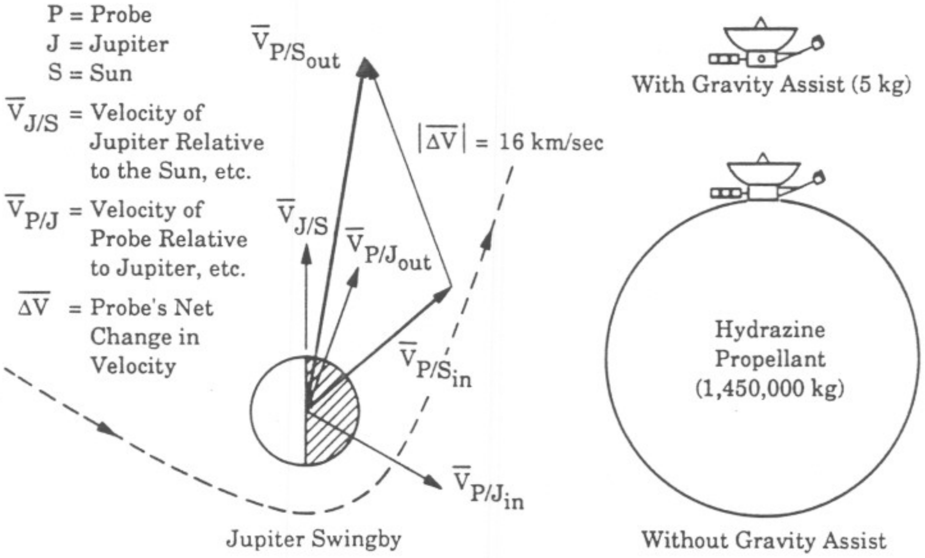


Figure 7-2. Passing close by a massive body causes a spacecraft's path to be bent, and energy to be exchanged between the spacecraft and body. In the Voyager-1 Jupiter swingby shown, there is no net speed gain relative to Jupiter; however, Voyager 1 gained 16 km/sec (35,700 mph) relative to the Sun, and Jupiter lost 1 foot per trillion years relative to the Sun, causing its orbital period to shrink by nearly one nanosecond.

the case of Voyager 2, this may be seen in Figure 11-6, which dramatically shows the behavior of the craft's Sun-relative speed as it swings past each of the Jovian giants enroute to escaping from the solar system. These principles also apply to gravity-assist applications using the large satellites of a planetary system.

Voyager 1 at Jupiter and Voyager 2 at Jupiter, Saturn, and Uranus passed by the trailing hemisphere of the respective planet, gaining speed at the expense of each planet. However, Voyager 1 passed (slightly) the leading hemisphere of Saturn, and Voyager 2 will pass (slightly) the leading hemisphere of Neptune. In these two cases, the spacecraft slowed down and the planets speeded up.

Diving for Triton

Neptune is Voyager 2's last planet. There being no next planet to seek (Pluto is not reachable; refer to Figure 6-2), Voyager 2 is not limited to passing Neptune through any particular gravity-assist corridor, and can instead concentrate on Neptune's large moon, Triton. Triton is as interesting to many planetary scientists as Neptune is. Triton is large enough to have an atmosphere. Its surface temperature and pressure are close to the triple point of nitrogen, raising the possibility of nitrogen clouds, frozen nitrogen *pools*, and snow/ice on the surface.

In 1980, Andrey Sergeyevsky discovered that there was indeed a way to pass closely by both Neptune and Triton, thereby maximizing the scientific return from each. The means was a final application of the gravity-deflection concept. The spacecraft would pass very close to Neptune (within 4850 kilometers of the cloud tops) in order to bend its path by about 45 degrees to pass close by Triton 5.2 hours later (see Figure 6-1.) The close passage of Neptune occurs near its North Pole, and is just barely on the leading hemisphere. Voyager 2 will slow down slightly (and Neptune will speed up even more slightly) as a result of this final gravity assist.

The Solar System is Ours

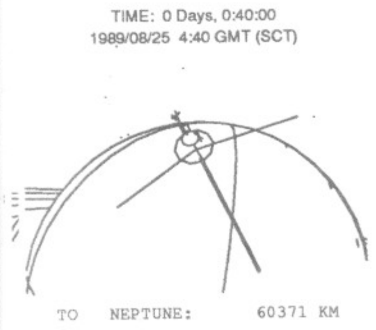
Before Minovitch applied his gravity-assist design concept, planetary spacecraft were limited to visiting Mercury, Venus, Mars, and Jupiter. Using gravity assist, missions to all the planets are possible. Spacecraft have travelled directly to Venus, Mars, and Jupiter. Mercury, Saturn, Uranus, and (as of the summer of 1989) Neptune have been visited via gravity assists. A mission to Pluto, using a Jovian gravity assist, will undoubtedly occur someday.

The next planned applications of the gravity-assist technique involve the use of planetary moons to provide the assist to planetary orbiters. Planetary systems that have large moons can be toured by using the gravity of the large moon(s) to deflect the spacecraft's orbit each time around.

The Galileo orbiter of Jupiter will perform ten gravity assists at Io, Europa, Ganymede, and Callisto, creating ten very close encounters of the latter three moons, and an additional three relatively close encounters. Galileo is due to launch in the fall of 1989, and will perform gravity assists at Venus (in 1990), and at Earth (1990 and 1992), before arriving at Jupiter in 1995.

On the drawing boards is a Saturn orbiter gravity-assisted touring mission. Forty gravity assists at Saturn's large moon Titan are planned for the Cassini spacecraft, leading to four very close passages and twenty-six relatively close passages of other Saturnian moons. Cassini is due to launch in 1996, and will perform gravity assists at the Earth (in 1998), and at Jupiter (in 2000), before arriving at Saturn in late 2002.

For more information on Galileo and Cassini, see Chapter 16.



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