The Spacecraft's Got Swing

An unmanned spacecraft will make a spectacular and controversial rendezvous with Earth this month. On August 16, the Saturn-bound Cassini probe will approach our planet's western hemisphere at about 35,000 miles per hour and, from a safe distance of about 725 miles, do-si-do with Earth's gravitational field. The maneuver, called a gravity assist, will increase Cassini's speed and send it reeling toward Jupiter and finally Saturn. The craft has made two earlier swingbys of Venus, wringing a little bit of energy from each encounter to build up the speed needed for its great leap toward the outer solar system. Its swingby with Earth this month will be no different. And despite the recent concern about the craft's reentry into our atmosphere, the gravity assist is crucial to Cassini's goal. Without the maneuver, the probe would never reach Saturn.

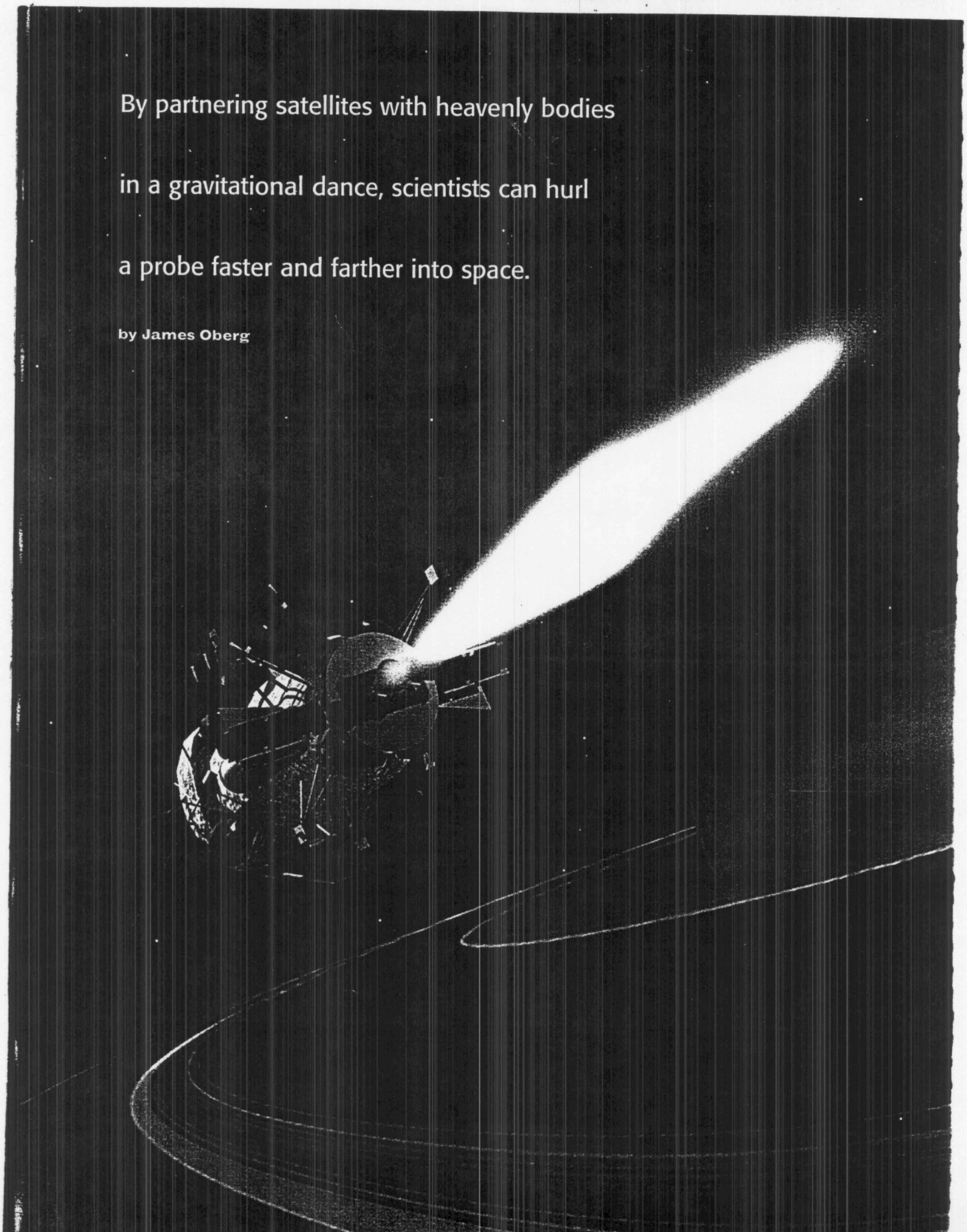
KINGS OF SWING

Cassini is not the first object to receive a gravity assist. Natural objects in our galaxy have experienced this phenomenon for millions of years. In the solar system, the wreckage from planetary births blundered around until it came into the gravitational clutches of planets. Many of the rocky pieces crashed into the massive bodies. But other space debris, just barely within the planet's grasp, got accelerated into the sun or flung along trajectories that broke free of the solar system entirely. The process continues today as a steady trickle of main-belt asteroids leaks into the inner solar system and is quickly — in a few tens of millions of years — swept out by random gravity assists from the planets. Comet astronomers of the 1800s were some of first to recognize these naturally occurring gravity assists. They noticed that when encountering a larger body, a comet appeared to change course slightly.

David Seal, Jet Propulsion Laboratory

By partnering satellites with heavenly bodies in a gravitational dance, scientists can hurl a probe faster and farther into space.

by James Oberg



In the 1920s, the Russian physicist Fridrikh Tsander described the maneuver, and during the 1960s, German engineer Krafft Ehricke, who worked on the V2 rockets with Wernher Von Braun during World War II, had outlined the mechanics of gravity assists in his book *Space Flight*. By the dawn of the Space Age, swingbys were fairly well known. In California, at NASA's Jet Propulsion Laboratory, graduate student Mike Minovitch devised a computer program that analyzed the possibility of using gravity assists on all possible missions. And at the same time and place, graduate student Gary Flandro was also working on a swingby plan. His trajectory proposed using the gravity of four planets to fling a spacecraft from one world to the next. But physicists and engineers at NASA headquarters remained skeptical about the technique.

"They were adamant this wouldn't work," says Flandro, who now works as a professor at the University of Tennessee Space Institute.

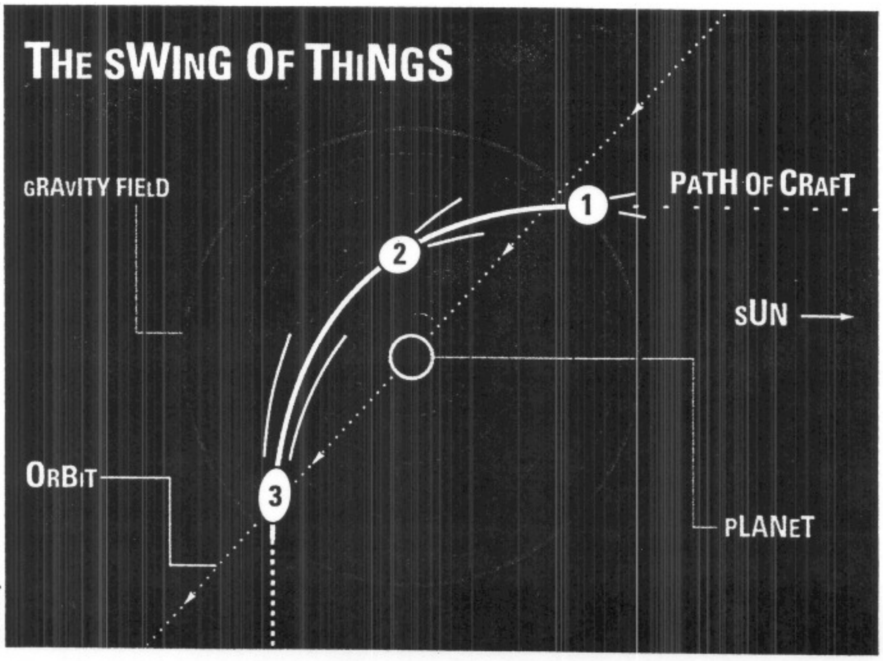
In hindsight, the skepticism seems ironic. At the same time NASA was raising its eyebrow at swingby technology, its own lunar probes were experiencing a similar phenomenon. Engineers soon realized that they could use the moon's gravity to shape the flight paths of spacecraft. Trajectory designers in Houston designed courses accordingly. They even devised emergency orbits, called free return paths, that used the moon's gravity instead of rocket maneuvers to send a craft back to Earth. In April of 1970, NASA used just such a flight path to bring the crippled Apollo 13 capsule back home safely. NASA was becoming more accepting of the possibility of gravity assists, but the real stamp of approval came in 1974 with Mariner 10. On February 5 of that year, engineers used Venus's gravity to slow Mariner 10's orbit, causing it to fall in toward the sun. That maneuver got Mariner close enough to the sun to swing past Mercury — something that had never been done before.

"By then, everyone had pretty well accepted it," says Flandro. "It opened up the whole solar system."

Indeed, the possibilities for exploration seemed remarkable, and NASA looked more closely at Flandro's plan. He had proposed a swingby route that took advantage of an unusual alignment of Jupiter, Saturn, Uranus, and Neptune. Each flyby would provide the velocity boost necessary to reach the next planet. The design not only economized by using one spacecraft, it also lowered the launch velocity and mission duration so the craft would arrive at Neptune decades earlier than would otherwise have been possible. But it was an arrangement that occurred only once every 176 years and would have to be taken advantage of by the late 1970s. NASA initially approved flybys of Jupiter and Saturn, and named the mission Voyager. Later they agreed to continue the funding to go on to Uranus and Neptune.

In 1989, Voyager 2 flew by Neptune to complete its "Grand Tour" of the solar system, fully vindicating the mathematical expectations of twenty years before.

Two things change during a gravity-assist maneuver: the spacecraft's speed and direction. If the spacecraft approaches from behind, gravity will not only accelerate the craft in the direction of the planet's revolution around the sun, but it will also pull the craft in arc around the planet. If the spacecraft flies in front of the planet, gravity will slow down the probe.



Astronomy: Terri Field

SWING LESSONS

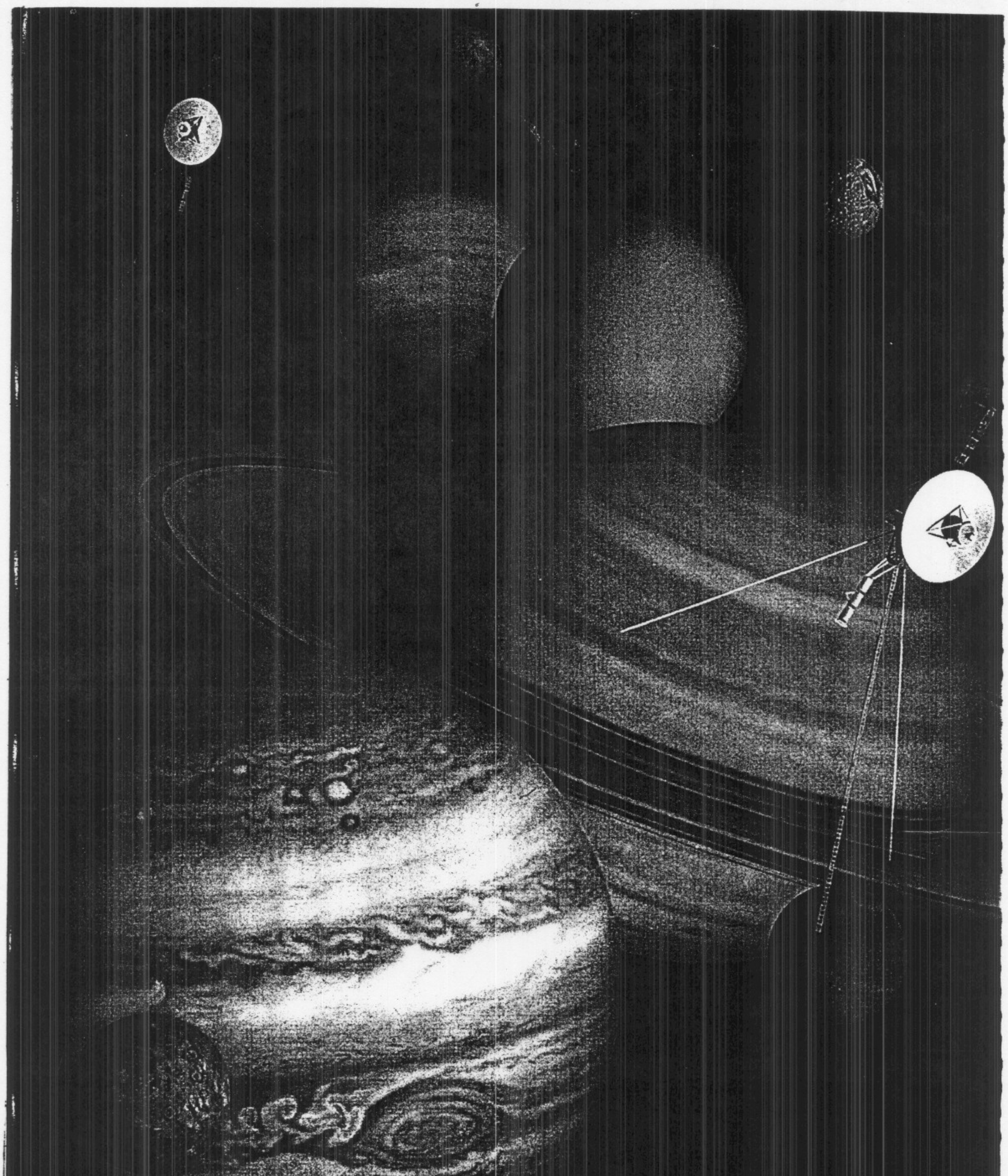
With the successful swingbys of Mariner 10, Voyager, and other spacecrafts, gravity assists gained validation. Trajectory designers began planning long, winding paths around planets to change the speed and direction of the vehicle. The routes added millions of miles to a craft's path, but in the end saved lots of rocket fuel — and consequently, money. In the case of Cassini, for example, engineers have designed a path that will take the probe a billion miles out of its way. But the gravity assists along the way will provide the energy equivalent to 75 tons of rocket fuel — a substantial boost for a ship that left Earth with only three tons.

"In the absence of a gravity assist, we would simply have to build a bigger rocket and launch it on a trajectory to go directly to the target," says Mitchell.

So how does a gravity assist work?

In simplest terms, a spacecraft exchanges momentum with a heavenly body to either speed up or slow down. Science fiction author Arthur C. Clarke offered a good analogy for this kind of exchange in momentum. He likened the maneuver to bouncing a ball off a moving wall. If you throw a ball at a stationary wall, the ball will rebound with about the same speed as it had before hitting the wall. Now imagine what happens if the wall is moving toward you. The ball rebounds with additional speed. The wall has transferred some of its momentum to the ball, causing it to speed up. And likewise, the ball has slowed the wall a negligible amount. The opposite occurs if the wall is moving away from you. A tossed ball rebounds with less speed. That's because the receding wall absorbs energy from the tossed ball,

Voyager flew by Jupiter, Saturn, Uranus, and Neptune to complete its "Grand Tour" of the solar system. Don Davis



causing it to slow down. And likewise, energy from the ball causes the wall to speed up a tiny amount.

On a flyby, spacecrafts and planets exchange momentum, too. To get an idea of what happens, imagine that you're riding in the front seat of a probe about to receive a gravity assist from Earth. From out in space, you see Earth in the distance and off to the left. It seems that you are on a course headed nowhere near the planet. But then the craft comes into Earth's sphere of influence, an imaginary realm encircling the planet where gravity has an affect. The force tugs on the vessel, causing it to diverge from its original course. At the same time, the spacecraft gains speed. As you veer closer to Earth, the force of gravity becomes stronger and the craft moves faster. At the same time, gravity is also altering the probe's trajectory, bringing it closer and closer to the planet. Over a span of time on closest approach, the change in velocity — a combination of speed and direction — sends the craft in a left turn around the planet. In addition, an exchange of momentum occurs between the craft and the planet, just as it gets exchanged between the ball and the moving wall. The spacecraft gains some of Earth's momentum while at the same time slowing down the planet a negligible amount.

According to Mitchell, Cassini will speed up by 11,000 miles per hour when it swings by Earth, and our planet will slow down by about 1 centimeter over about 2 million years. The curious thing is that from our planet's frame of reference, the space probe arrives and departs with exactly the same speed. Since we're moving too, we don't notice the momentum we add to the craft. But if we could stand on the sun and watch the event, we would see Cassini gain Earth's momentum and speed up.

FINDING A GOOD PARTNER

For any gravity assist, the determining factor in the magnitude of the speed change is the size of the planet and the approach speed of the spacecraft. The gravity from Jupiter will exert more force on a spacecraft than the gravity of our moon, for example. Another factor is the craft's flyby geometry. Objects that pass behind the planet will become caught in the planet's forward momentum and gain speed. But those that pass in front of the planet will get tugged in the opposite direction and slow down.

As a result, trajectory designers can vary the flyby geometry to produce a combination of maneuvers involving a change in velocity. They must also consider the geometry of the path with regard to the planet — don't hit the rings! These parameters are tied together, so often the planners have to balance the desired results against the necessary consequences. The number of variables have made many missions possible. The finest example is Galileo's tour of the jovian moons. About every two months beginning in December 1995, the probe made a close flyby of Ganymede, Callisto, or Europa, and it will be approaching Io again late this year. Flyby distances at each moon ranged from 120 miles to several thousand miles, and each encounter resulted in a new direction and speed.

The price paid for gravity assists is usually mission complexity. They often require a sequence of planet encounters in order to build up adequate velocity for reaching the outer solar system, for changing orbital planes enough to reach comets and asteroids, and for getting closer to the sun. In the future, advanced high-efficiency engines may allow interplanetary missions to proceed directly to their targets. But for now, engineers continue to develop new and more-sophisticated gravity-assist missions.

One of them involves the Japanese spacecraft, the Nozomi Mars probe. It pioneered a gravity-assist trajectory using a highly elliptical Earth orbit and a series of lunar flybys. These allowed scientists a much bigger launch window in which to put the probe on course for Mars. In a few years, the same path will be used by a whole new class of small Ariane-V-launched Mars hitchhiker payloads. Nozomi, meanwhile, botched its rocket burn last December 20 and used up so much maneuvering fuel that its normal Mars orbital mission became impossible. However, by using a series of gravity assists from Mars and two from Earth (becoming the first space vehicle to make the Earth-Mars-Earth round-trip), it will be able to creep up on Mars much more gently in about four years to complete its mission. In the future, space hotels — which will consist of the heaviest life-support components needed for the months-long voyages — may repeatedly traverse the very same Earth-Mars route to carry people back and forth between the planets.

The entire idea of gravity assist missions is a wonderful example of how, while we still can't break or even bend the laws of gravity, we can invent clever new ways to exploit those laws, to find the loopholes and send our spacecraft — and eventually ourselves — along those hitherto uncharted paths. ◼

James Oberg is a veteran space flight expert and writer residing in Texas, who has been contributing to Astronomy *since 1974. His home page is www.jamesoberg.com.*

DANCING WITH THE MOON

Forty years after Earth's governments began sending probes to the moon, a U.S. corporation followed the path blazed by the Luniks, Pioneers, Apollos, and Zonds. In May of last year, Hughes Space and Communications Company salvaged a failed satellite orbit and made history with the first commercial mission to the moon.

Hughes had built the HGS-1 satellite for Asiasat, an Asian telecommunications consortium. During liftoff, the launch rocket malfunctioned, placing the craft in an unusable, highly elliptical orbit over Earth. There was a small amount of reserve fuel left, but it was not enough to make the necessary orbital change.

The company was about to write off the satellite as a loss. But orbital planners at Hughes refused to give up. They drew up plans to send the satellite toward the moon, where gravity could help reposition the craft's orbit. On May 13, 1998, the satellite made its first swingby of the moon. Lunar gravity twisted the craft's orbital plane and raised it up to the desired level. A second swingby on June 6 improved the craft's orbit to near perfection.

"The lunar recovery mission team did an outstanding job," says the company's president, Ronald Swanson. "It really validates the viability of this technique for future missions." — *J. O.*

The HGS-1 satellite was the first commercially owned craft to receive a gravity assist — in this case, from the moon.

Hughes Space and Communications Company