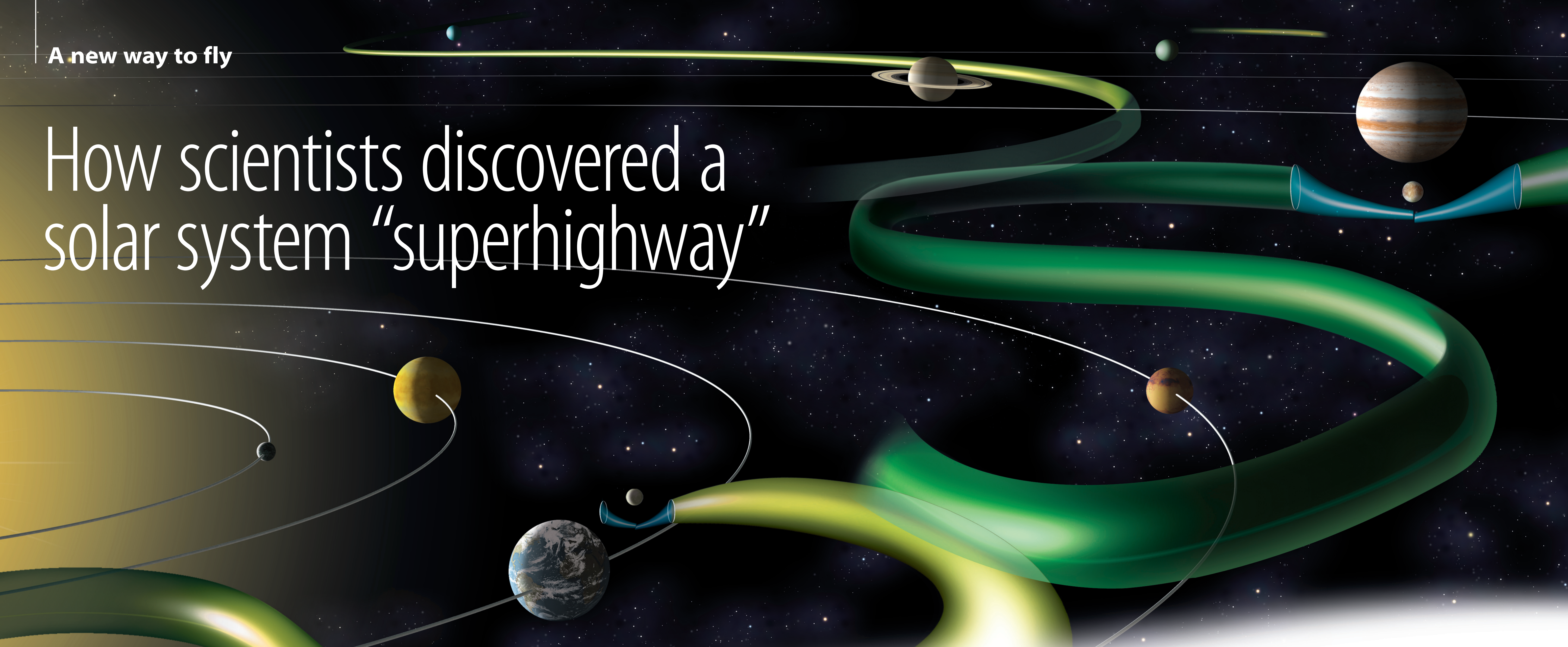
A new way to fly

How scientists discovered a solar system “superhighway”



Spacecraft can travel far and wide in the solar system by riding gravitational currents between every planet and moon. Gravity does the heavy lifting on these journeys, so the craft can carry less propellent. *Astronomy:* Roen Kelly

By riding planetary gravity, spacecraft can explore the solar system without using fuel. **by Francis Reddy**

During the past decade, researchers working to improve how spacecraft navigate have discovered an underlying structure in the solar system. But it isn’t the vast cosmic clockwork that English physicist Sir Isaac Newton envisioned, with planets and moons orbiting the Sun in stately precision.

Instead, this new solar system is a complex, dynamic structure of swirling and interconnecting pathways shaped by the mutual gravitation of all the planets and moons. These passages constitute a natural transportation network that enables anything — dust, meteorites blasted off of planets, asteroids, comets, and spacecraft — to move throughout the solar system with ease. “We call it the Interplanetary Superhighway,” says Martin Lo, a researcher at NASA’s Jet Propulsion Laboratory (JPL) in Pasadena, California.

Many spacecraft have already traveled the Interplanetary Superhighway (IPS). They include NASA’s Genesis and Wilkinson Microwave Anisotropy Probe (WMAP) spacecraft, and the European Space Agency’s SMART-1 lunar orbiter.

The IPS is no expressway: Even though missions save fuel, they can take much longer to reach a target than they would by using chemical rockets. However, if you’re willing to wait, a longer journey results in big savings of a spacecraft’s most precious commodity: propellant. And that means science probes could travel farther afield at lower cost, opening up new possibilities for exploration in virtually any destination in the solar system.

Easy rider

Key factors dictate the fuel needs for conventional spacecraft missions. “It depends on how far apart the destinations are that you want to visit, the length of time you want to stay there, and the number of instruments you carry on board,” says engineer Shane Ross at Virginia Tech in Blacksburg, Virginia. Ross worked with Lo in mapping out the IPS.

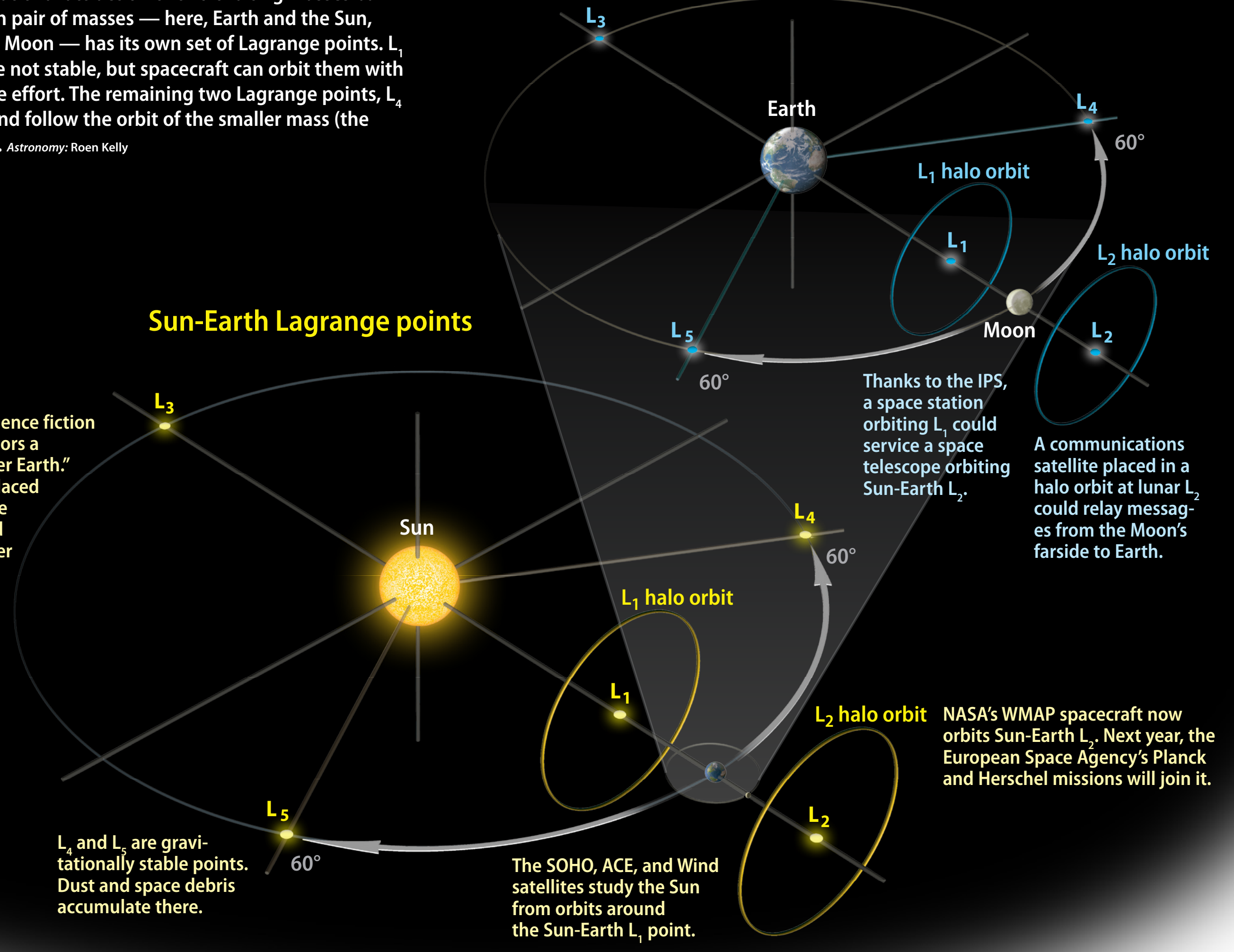
Take, for example, Voyager 1, now the farthest and fastest spacecraft in the solar system. Fuel made up nearly half of its initial mass. Although JPL mission planners used gravitational boosts to speed Voyager from Jupiter to Saturn and then out of the solar system, the craft still had to burn propellant to fine-tune its trajectory. The fuel problem gets worse for orbiters and landers, which must bleed off much of their original speed when they reach their destinations.

The IPS provides a way around this. Now it’s possible to design trajectories that take advantage of the complex interplay of gravitational forces from multiple planets and moons. The resulting passages follow what are, in essence, gravitational currents that flow throughout the solar system.

The IPS can take spacecraft anywhere, Ross says. “If you launch from the surface of any planet or moon with the right

Gravitational balance points

Lagrange points are five locations (L_1 through L_5) where the mutual gravitational attraction of two orbiting masses balance out. Each pair of masses — here, Earth and the Sun, Earth and the Moon — has its own set of Lagrange points. L_1 through L_3 are not stable, but spacecraft can orbit them with relatively little effort. The remaining two Lagrange points, L_4 and L_5, lead and follow the orbit of the smaller mass (the Moon) by 60°. *Astronomy:* Roen Kelly



Thanks to the IPS, a space station orbiting L_1 could service a space telescope orbiting Sun-Earth L_2.

A communications satellite placed in a halo orbit at lunar L_2 could relay messages from the Moon's farside to Earth.

In a class of science fiction stories, L_3 harbors a hidden "counter Earth." But a planet placed in this unstable location would actually wander off in a few months.

NASA's WMAP spacecraft now orbits Sun-Earth L_2. Next year, the European Space Agency's Planck and Herschel missions will join it.

L_4 and L_5 are gravitationally stable points. Dust and space debris accumulate there.

The SOHO, ACE, and Wind satellites study the Sun from orbits around the Sun-Earth L_1 point.

speed and direction, or start in the right orbit around any planet or moon, you can eventually get to the surface or in orbit about any other planet or moon." The IPS can even take probes out of the solar system, given enough time.

Balance points

Lo, Ross, and Caltech's Jerrold Marsden and Wang Sang Koon began mapping out the IPS using key ideas from various branches of mathematics. One is the existence of gravitational balance points between any two orbiting bodies.

For every pair of masses, their gravitational forces strike a balance at five locations. Two of these spots are so stable they can trap dust or asteroids. Although the other locations are unstable, mission designers realized decades ago that spacecraft can maintain orbits around them with little effort.

Scientists discovered these balance points in the 18th century. The Swiss mathematician Leonhard Euler (1707–1783) identified the first three, dubbed L1, L2, and L3. These points lie along a line joining the two orbiting masses.

Later, French mathematician Joseph-Louis Lagrange (1736–1813) discovered two more balance points: L4 and L5. They lie along the orbit of the smaller mass, leading and following its motion by 60°. Scientists now refer to all of these locations as Lagrange points.

Unstable options

Matter placed at L1, L2, and L3 will linger but eventually drift off — these points aren't stable. But orbital motion helps corral objects at L4 and L5. The best example: There are 2,500 Trojan asteroids ensnared at Jupiter's L4 and L5 points.

Most scientific interest has focused on L4 and L5. For example, a famous 1975 study by Princeton University's Gerard K. O'Neill determined L5 to be the preferred location for a permanent space colony.

Stability counts for a lot if you want to keep something in one spot. But if you want to travel around the solar system, the unstable Lagrange points are a lot more interesting. It's a characteristic of instability that a little change can produce a major effect down the road.

In 1961, meteorologist Edward Lorenz dubbed this sensitivity to initial conditions the "butterfly effect" after noticing that computer-based weather forecasts produced wildly different results with only slight changes in starting conditions. Carried to its extreme, he said, the flapping of a butterfly's wings in one part of the world could alter the weather in another. Mathematicians developed what they call "chaos theory" to describe such systems.

Precisely because they're dynamically unstable, the L1 and L2 points constitute the IPS equivalent of highway interchanges. Near these points, the tiniest nudge from a thruster could send a spacecraft on entirely new trajectories. "There are paths that approach the Lagrange points, orbit around them, head off on an orbit around the Sun, and then come back," Ross says. "The possibilities are mind-boggling."

Corraling complexity

The tools needed to make a road atlas of the IPS — and develop modern notions about mathematical chaos — began with the work of Jules-Henri Poincaré (1854–1912). The French mathematician was searching for an exact solution to the so-called three-body problem: What are the orbits of three masses interacting gravitationally in space?

He didn't find it — no one has. Thanks to the complex interplay of ever-shifting forces, the three-body problem is a tough one to solve. Even with simplifications like restricting all bodies to the same plane or making one of the masses vanishingly small, the three-body problem remains daunting. But Poincaré found a way to corral the complexity.

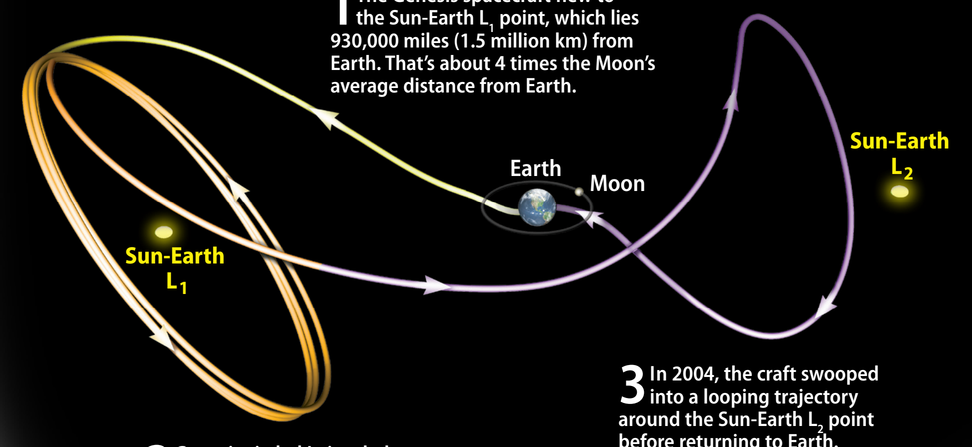
Poincaré saw that families of similar orbits lie on smooth surfaces called manifolds. Unless the orbiting object's energy changes — say, by firing a thruster — it forever remains on the same surface. Easy enough, but the tough part is understanding that these structures exist in six dimensions — up-down, left-right, forward-back, plus a dimension for the object's speed in each direction.

Poincaré noticed something interesting about unstable periodic orbits — the kind a spacecraft at L1 or L2 might experience. Such orbits generate tube-shaped manifolds that contain all of the paths the craft could follow to drift out of its orbit without changing energy (by, say, firing a thruster). This is the orbit's unstable manifold. And there's another tube — the stable manifold — that contains all of the paths that can place the spacecraft onto its current orbit with no energy change.

Because people live in three-dimensional space, it's hard to get your head wrapped around mathematical manifolds in a six-dimensional universe. But, in essence, these manifolds constitute the IPS' off-ramps and on-ramps.

Genesis' loopy journey

The Genesis mission left Earth in 2001 to sample the solar wind. It flew millions of miles using relatively little fuel by following a trajectory in which gravitational influences created a "path of least resistance" through space. *Astronomy:* Roen Kelly



1 The Genesis spacecraft flew to the Sun-Earth L_1 point, which lies 930,000 miles (1.5 million km) from Earth. That's about 4 times the Moon's average distance from Earth.

2 Genesis circled L_1 in a halo orbit for 2½ years while sampling charged particles streaming from the Sun.

3 In 2004, the craft swooped into a looping trajectory around the Sun-Earth L_2 point before returning to Earth.

Homing in on Lagrange

Groundbreaking on the IPS began in 1966, when Stanford University graduate student Robert Farquhar described orbits around Earth-Moon L2, the balance point behind the Moon. A satellite in such an orbit could continuously relay data and messages from Earth to the lunar farside, where communication would otherwise be impossible.

Farquhar called these paths halo orbits because, seen from Earth, a satellite would slowly trace a halo-like circle around the Moon. Seen from space, a halo orbit resembles the edge of a potato chip centered on the Lagrange point.

A few years later, Farquhar persuaded NASA to fly the first mission to a Lagrange point. His team found a pathway that placed the International Sun-Earth Explorer 3 (ISEE-3), launched in 1978, into a halo orbit at Earth's L1 point (the balance point between Earth and the Sun). This gave the spacecraft a continuous view of the Sun and allowed ISEE-3 to monitor the "wind" of charged particles streaming from it.

Without knowing it, Farquhar's team was the first to road test the IPS. Any path they chose to put ISEE-3 into a halo orbit around Sun-Earth L1 would inevitably follow this point's stable manifold. Pictured in six dimensions, the craft's orbit traced a lazy spiral around the tube's surface, naturally spooling ISEE-3 into its halo orbit. The probe could also spiral out of its halo orbit along the unstable tube.

And that's just what the mission controllers did. In 1982, with its primary mission complete, ISEE-3 went on to accomplish other goals. By combining five lunar flybys with broad loops around Sun-Earth L2, the probe gained enough

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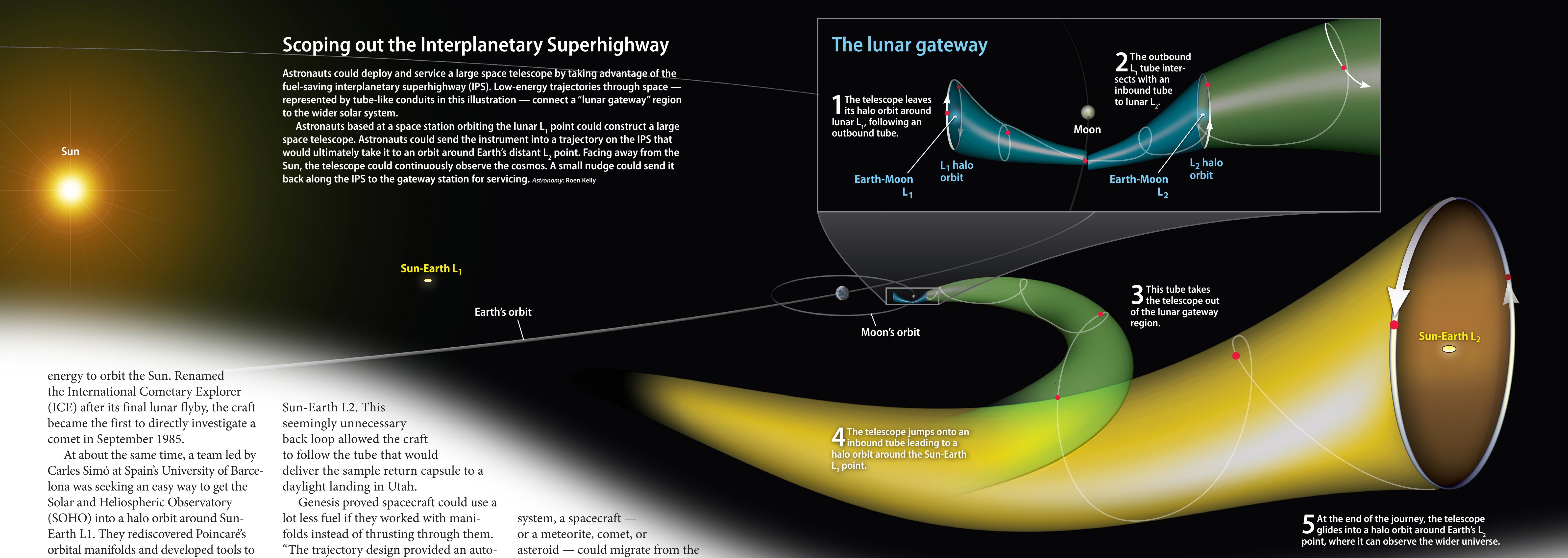

Scoping out the Interplanetary Superhighway

Astronauts could deploy and service a large space telescope by taking advantage of the fuel-saving interplanetary superhighway (IPS). Low-energy trajectories through space — represented by tube-like conduits in this illustration — connect a “lunar gateway” region to the wider solar system.

Astronauts based at a space station orbiting the lunar L$_1$ point could construct a large space telescope. Astronauts could send the instrument into a trajectory on the IPS that would ultimately take it to an orbit around Earth's distant L$_2$ point. Facing away from the Sun, the telescope could continuously observe the cosmos. A small nudge could send it back along the IPS to the gateway station for servicing. *Astronomy:* Roen Kelly

1 The telescope leaves its halo orbit around lunar L$_1$, following an outbound tube.

2 The outbound L$_1$ tube intersects with an inbound tube to lunar L$_2$.

3 This tube takes the telescope out of the lunar gateway region.

4 The telescope jumps onto an inbound tube leading to a halo orbit around the Sun-Earth L$_2$ point.

5 At the end of the journey, the telescope glides into a halo orbit around Earth's L$_2$ point, where it can observe the wider universe.

energy to orbit the Sun. Renamed the International Cometary Explorer (ICE) after its final lunar flyby, the craft became the first to directly investigate a comet in September 1985.

At about the same time, a team led by Carles Simó at Spain's University of Barcelona was seeking an easy way to get the Solar and Heliospheric Observatory (SOHO) into a halo orbit around Sun-Earth L1. They rediscovered Poincaré's orbital manifolds and developed tools to compute flight paths based on them.

Mission designers began to take notice. One of them was Martin Lo. He wondered how far these tubes extended from the Lagrangian gateways, and where they ultimately ended up. Was it possible to go from one planet to the next?

Genesis rides the IPS

At the time, Lo and Purdue University astronautical engineer Kathleen Howell were planning the trajectory for NASA's Genesis mission to return samples of the solar wind to Earth. Genesis launched in August 2001, cruised for 3 months to Sun-Earth L1, and fired its thrusters for almost 5 minutes to insert itself into a halo orbit. In December, the craft opened its collector arrays and began gathering solar wind particles. It completed five halo orbits over the next 30 months.

In April 2004, Genesis battened down its sample-collector hatch, spooled off the halo orbit, and headed home. Over the next 5 months, the craft would pass Earth and then loop behind it around Sun-Earth L2. This seemingly unnecessary back loop allowed the craft to follow the tube that would deliver the sample return capsule to a daylight landing in Utah.

Genesis proved spacecraft could use a lot less fuel if they worked with manifolds instead of thrusting through them. “The trajectory design provided an automatic halo departure and return to Earth,” Lo explains. “Genesis wouldn't have needed to use any fuel at all in a perfect world. But, practically, there are always small navigation maneuvers to correct tiny errors in our knowledge of the spacecraft's speed or position.”

Tube hopping

Perhaps the most exciting aspect of the IPS is this: A spacecraft can use it to easily transfer from one planet's sphere of influence to another's. Picture the manifolds arcing from each planet's Lagrange points as the swirl of water spraying from a lawn sprinkler. They're in constant motion as the planets and moons that create them ply their paths in space. When the tubes from one planet intersect those of another, low-energy transfers between the two worlds become possible.

In 1996, Lo and Ross demonstrated that tubes from Jupiter's and Saturn's Lagrange points intersected every couple of decades. Further work showed that all of the planets were so linked. Using this system, a spacecraft — or a meteorite, comet, or asteroid — could migrate from the Kuiper Belt to the asteroid belt, or vice versa, in a matter of a few hundred years.

This ability of objects to effortlessly navigate the solar system explains some puzzling behaviors. In 1943, astronomers discovered Comet 39P/Oterma orbiting inside of Jupiter's orbit. The comet circled the Sun three times for every two Jupiter orbits (a 3:2 resonance). But in 1963, Oterma swept within 9.3 million miles (15 million kilometers) of the planet and ended up in a 2:3 resonance beyond Jupiter.

It turns out that Oterma's inner orbit skirts the Sun-Jupiter L1 point, while the comet's outer orbit brushes past the Sun-Jupiter L2. Instead of traveling on the surfaces of orbital tubes, Oterma has been lumbering into them and riding them past the planet.

During these close approaches, the comet performs a Jupiter gravity assist much as the Voyagers did. “Both the comet and the spacecraft took advantage of tubes associated with resonant orbits,” Lo says. Each time Oterma sweeps through the jovian tubes, the rules of mathematical chaos determine where it ends up next.

Mapping the highway

Lo and his colleagues have shown that mission planners can pick an itinerary for any pair of Lagrange points and a trajectory exists that will follow it. The possibilities have excited a lot of other scientists. Lo's team is now fine-tuning software to develop better maps of the solar system's gravitational currents. Many weird families of orbits have yet to be studied in detail.

“The paths we've looked at previously have been ‘free fall’ paths, meaning it just takes into account Newton's law of gravity and how planets and moons are moving,” Ross says. Mission planners would like to combine the IPS “free ride” with powered flight to get the best of both worlds. For example, a journey could use conventional brute-force thruster power to get to Jupiter's realm relatively quickly, then use the IPS to hop from orbits around different moons. Such a mission already exists on paper.

One IPS application Lo has looked at in detail is building a space station at Earth-Moon L1 to serve as a transportation hub. Any future space telescope would be an ideal commuter. The instrument could be constructed conveniently at nearby lunar L1 and, when complete, shipped via the IPS to Sun-Earth L2.

From there, the telescope would face outward from the Sun and Earth at what is widely seen as astronomy's new mountaintop. Later, if the telescope needed repairs or upgrades, a gentle nudge could send it back through the IPS to the service station at Earth-Moon L1.

Farther ranging destinations are also possible. “The station would also be an excellent staging area for human or robotic missions to the asteroids, Mars, giant planets, and beyond,” Ross notes.

Newton's solar system was is a model of cosmic order, Poincaré's is one ruled by chaos. Using insights gleaned from three centuries of studying gravity, the IPS could bring humanity's presence more rapidly, routinely, and completely into space than anyone imagined even a decade ago.

Watch an animation of a space telescope's journey on the IPS, narrated by Martin Lo, at www.Astronomy.com/toc.