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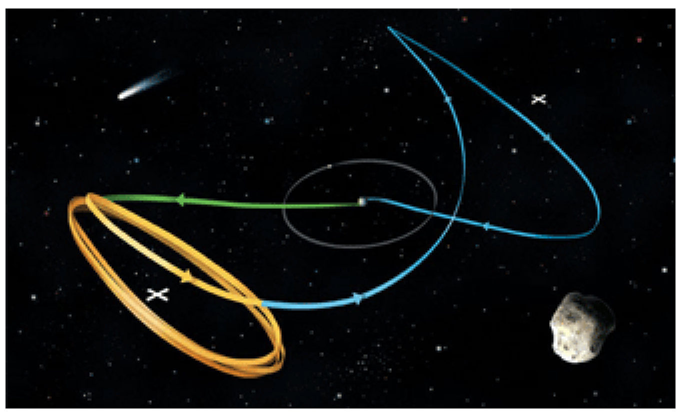
Space Travel:
Mathematics Uncovers an Interplanetary Superhighway

By Dr. Shane Ross

Contrary to everyday experience on Earth, the most efficient route through space may not be a straight line. To take best advantage of gravity, and save fuel in the process, it may be necessary to make bizarre loops through space. This is what some mathematicians and NASA engineers have learned in recent years.



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Getting from point A to B in space usually requires considerable quantities of propellant. But after it blasted off from Earth, the Genesis probe was able to travel 1.5 million kilometers. More...

Take for example the Genesis spacecraft. In 2004, it started on its way home after having spent two years collecting solar particles in orbit around a Lagrange point, a point between Earth and the Sun where the gravity of both bodies is balanced.

But Genesis did not come straight home. It took a long curvy path, going past the Earth to make an extended million mile loop (around another Lagrange point) before coming back to Earth. Amazingly, this seeming impractical path actually saves fuel by making use of gravity in the Earth-Sun system.

The design of interplanetary space probes can now be done by taking advantage of the competing gravitational tugs of the different planets and their moons, which create a vast network of passageways by which a spacecraft can travel over large distances while expending very little energy. Without recent advances in mathematics and computation, these fuel-saving, mission enabling, paths through space could not be found.

Click the links to the right to learn more about the gravitational passageways which form this interplanetary transport network.

About the Author

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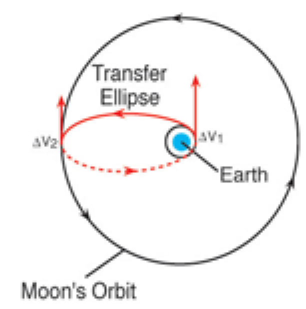
Mission Design

To have a space mission that can actually fly, you need to find a path through space connecting an initial orbit and a destination orbit. And you need to do this using a reasonable amount of fuel. Think about going from Earth orbit, like the one the International Space Station is in, to an orbit around the Moon.



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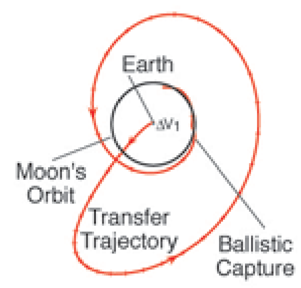
You could try getting there in a straightforward way, using an elliptical transfer trajectory from the Earth to the Moon. An upper stage rocket can supply the first large maneuver which burns an amount of fuel proportional to the change in velocity, or ΔV, imparted to the spacecraft. But as it hurtles away from the Earth, the spacecraft still has to have enough on-board fuel to perform a pretty large rocket burn, labeled ΔV_2, to get caught into an orbit around the Moon.

A less obvious trajectory to the Moon uses the gravity of the Earth, Moon, *and Sun*. Heading out about four times further than the Moon's orbit, the spacecraft feels a curious combination of the Earth and Sun's gravity. The effect is to guide the spacecraft into an orbit around the Moon for free, or "ballistically" in spaceflight lingo. This trajectory uses significantly less on-board fuel than the straightforward approach, but requires more flight time.



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Some previous space missions have used this rich interplay of several gravitational fields. By understanding the mathematics governing the paths such missions use, other interesting future missions can be designed, not only in the Earth-Moon system, but around other planets and moons in the solar system.

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The Importance of ΔV

Space scientists use ΔV, which is simply the change in velocity, to measure the amount of fuel it takes to do a rocket burn maneuver. The lower the total of the ΔV's, the less fuel a mission will take. It takes a lot of fuel to put on the brakes at a destination planet or moon to get into orbit, observe for a while, and then blast off to the next destination, and so on. The overall mass of a spacecraft cannot go beyond the limits set by what modern rockets can launch into Earth orbit. So a balance must be struck between a mission's proposed itinerary and the quantity of instruments it can carry. Missions such as Galileo and the Apollo Lunar Lander consumed between 40 and 60 percent of their mass in fuel.

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Previous Mission Trajectories

Mission designs have a common problem: fuel. Fuel, or propellant, is a major factor limiting a spacecraft's journey. Fuel needs rise dramatically depending on how far apart the destinations are you want to visit, the length of time you want to stay there (in orbit), and the number of instruments you carry on board. One way around this is to design space mission trajectories which use the complex interplay of gravitational forces from multiple bodies. This leads to trajectories which either can't be designed using "straightforward" methods or are very fuel efficient compared to a straightforward approach. Some examples are listed below.

International Sun-Earth Explorer/International Cometary Explorer

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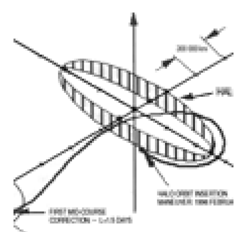
In 1972, the International Sun-Earth Explorer (ISEE) Program was estabilished, a joint project of NASA and the European Space Agency (ESA) which was to involve three spacecraft. One of these, ISEE-3, was launched into a halo orbit around the Sun-Earth L_1 point in 1978, allowing it to collect data on solar wind conditions upstream from Earth. ISEE-3 accomplished many scientific goals. After the primary mission was completed, ISEE-3 went on to accomplish other goals, including a flight through the geomagnetic tail and a comet flyby, by utilizing the interesting dynamics in the Sun-Earth-Moon system. The mission was subsequently renamed the International Cometary Explorer (ICE).

Solar and Heliospheric Observatory



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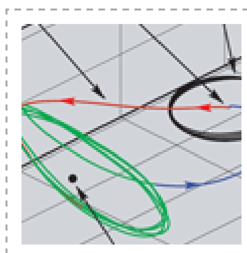
In the mid-1980s, a team in Barcelona were the first to study the invariant manifolds of halo orbits and apply them to the design of a space mission, in particular the Solar and Heliospheric Observatory (SOHO) mission. SOHO is a mission designed to study the internal structure of the Sun, its extensive outer atmosphere and the origin of the solar wind, the stream of highly ionized gas that blows continuously outward through the solar system. It is a joint project of the European Space Agency (ESA) and NASA.

Genesis Discovery Mission



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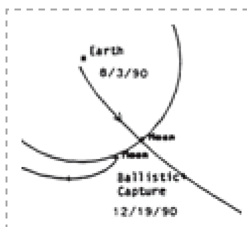
The Genesis spacecraft collected solar wind samples from a halo orbit about the Sun-Earth L_1 point for two years, returning them to Earth via a sample-return capsule which returned to Earth in September 2004 for analysis and examination. The solar wind was imbedded in a set of ultra-pure material collectors the size of bicycle tires that were deployed throughout the collection phase of the mission. The sample is the only extraterrestrial material brought back to Earth from deep space since the last of the Apollo landings in 1972, and the first to be collected from beyond the Moon's orbit. Ongoing analysis of the samples collected by the mission will contribute to our understanding of the origins of the solar system.

Hiten (MUSES-A)



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The first example of a low-fuel path to the moon was the rescue of a malfunctioned Japanese space mission to the Moon by Belbruno and Miller of NASA's Jet Propulsion Laboratory in June 1990. The mission originally had two spacecraft, MUSES-A and MUSES-B; B was to go into orbit around the Moon, with A remaining in Earth orbit as a communications relay. But B failed and A did not have sufficient fuel to make the journey. However, by utilizing a trajectory concept originally discovered by Belbruno in 1986, which is more energy-efficient than the one planned for B, MUSES-A (renamed Hiten) left Earth orbit in April, 1991 and reached the Moon that October. As a result, Japan became the third nation to send a spacecraft to the Moon. After a series of scientific experiments, Hiten was purposely crashed into the Moon in April, 1993.

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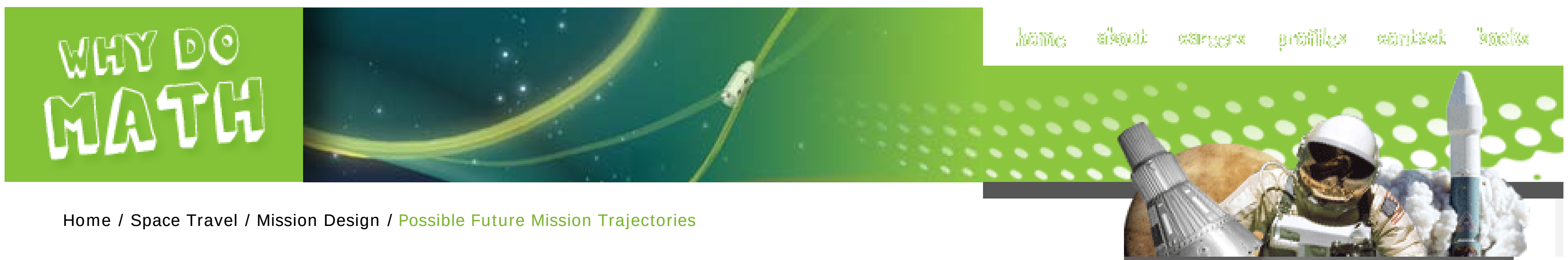

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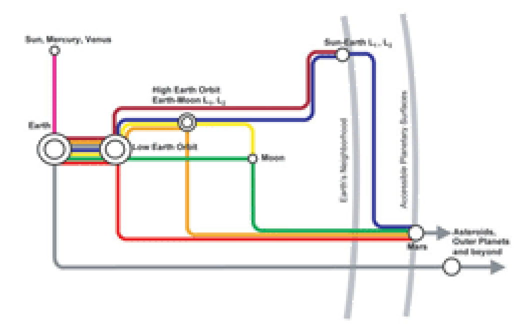
Possible Future Mission Trajectories

Lunar L_1 Gateway Station

For instance, NASA desires to develop a robust and flexible capability to visit several potential destinations. The figure shows in "metro map format" some connections between hubs in Earth's neighborhood and beyond. It has been recognized that in addition to orbits around planets, orbits around the Lagrange points L_1 and L_2 in both the Sun-Earth and Earth-Moon system are important hubs and/or destinations.



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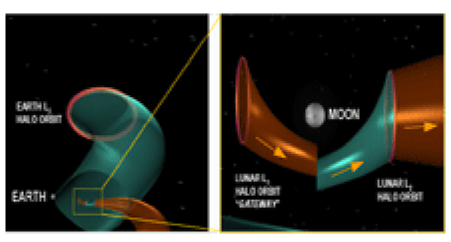
A metro map representation showing hubs connected by gravitational passageways in the near-Earth neighborhood and beyond. More...

In fact, the fortuitous arrangement of natural gravitational passageways in near-Earth space implies that Earth-Moon L_1 and L_2 orbits are connected to orbits around the Sun-Earth L_1 or L_2 via natural low-fuel pathways. A future Lunar L_1 Gateway Station at the Earth-Moon L_1 Lagrange point (between the Earth and Moon) has been proposed as a transportation hub beyond low-Earth orbit. Future deep space telescopes could be built in the micro-gravity environment of the Station and may be built in a lunar L_1 orbit and conveyed to the deep space environment of the Sun-Earth L_2 point with minimal fuel requirements.



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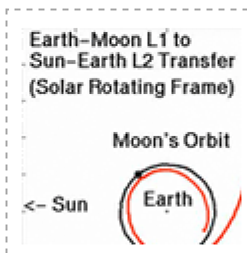

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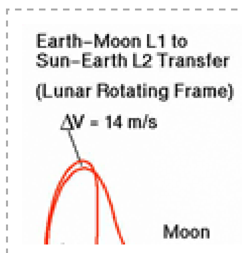

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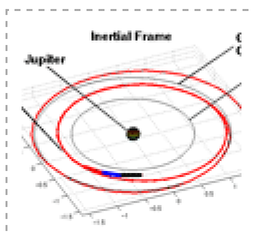
The station would also be an excellent staging area for other deep-space missions, human or robotic, to the asteroids, Mars, giant planets, and beyond.

Multi-Moon Orbiters of Jupiter's Icy Moon

There has been much recent interest in sending a spacecraft to perform extended observations of several of Jupiter's moons. Europa is thought to be a place hospitable to life because of the vast, liquid oceans that may exist under its icy crust. Two other Jupiter moons, Ganymede and Callisto, are now also thought to have liquid water beneath their surfaces. A proposed mission to Europa, and perhaps also Ganymede and Callisto, would attempt to map these regions of liquid water for follow-on missions.

A "Petit Grand Tour" of the Jupiter moon system is shown in the animations. This is an example of a *multi-moon orbiter* mission in which a single scientific spacecraft orbits several moons of Jupiter (or any of the outer planets' moons). Using this approach, long duration observations are possible instead of flybys lasting only seconds. A multi-moon orbiter could orbit each of the planet-sized moons of Jupiter--Callisto, Ganymede, Europa, and Io--one after the other, using a technologically feasible amount of fuel.



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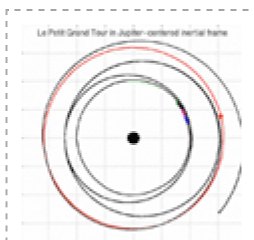
Petit Grand Tour trajectory



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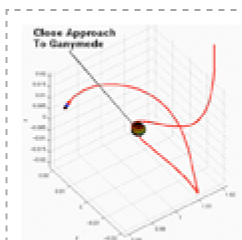
Petit Grand Tour trajectory seen projected onto the orbital plane of Europa and Ganymede



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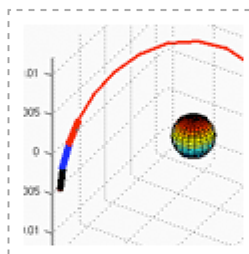
Ganymede loop-de-loop



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Europa orbit insertion

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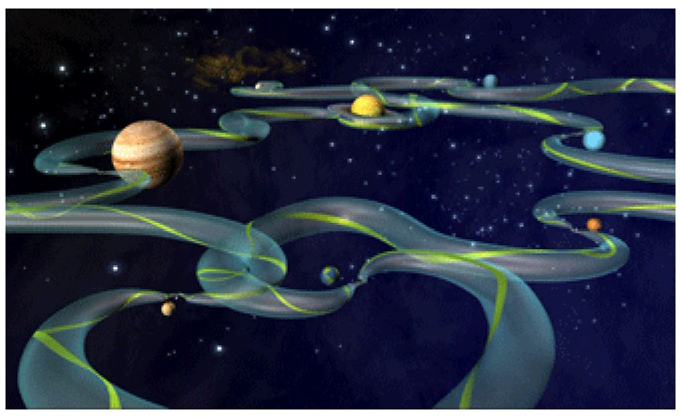
The Mathematics

The mathematical study of how artificial and natural objects move in the solar system is celestial mechanics. Closely related to celestial mechanics is the subject of dynamical systems, which interprets the motion of an object using geometry. There are three key ideas from celectial mechanics and dynamical systems that are used to reveal the interplanetary transport network.

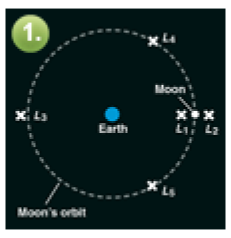


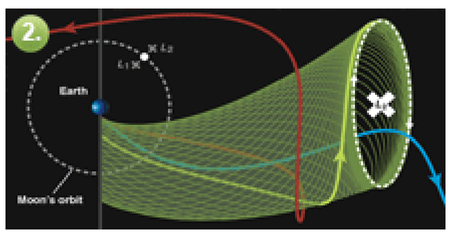
The interplanetary transport network. Gravitational tugs of the different planets and their moons create a vast network of passageways by which a spacecraft can travel over large distances while expending very little energy. More...

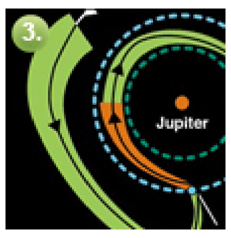
The first idea (1) is the existence of Lagrange points, points in space where the net forces on an object placed at that point are zero. Spacecraft can even go into orbit around a Lagrange point, even though the point has no mass.

The second idea (2) is that here are tubes of trajectories which approach and depart Lagrange point orbits; they're called stable and unstable manifolds.

The third idea (3) is that the many planets and moons create a network of these tubes twirling through space which are well suited to space travel. Where two different tubes intersect, one has a heteroclinic trajectory. If a spacecraft is placed on such a trajectory, it will move a large distance under the influence of gravity and without the use of any fuel.







So it is possible for a spacecraft to travel huge distances in space just by hopping from the neighborhood of one Lagrange point to another.

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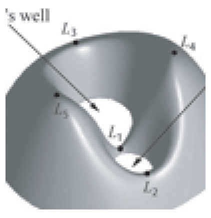
Lagrange Points



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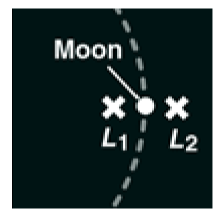
In a system consisting of two celestial bodies, say the Earth and the Moon, the combined gravitational wells of the two bodies produce a potential energy surface like the one at left, as seen in a frame of reference turning with the two bodies in their orbit. For over two hundred years, it's been known that there are five points of equilibrium, named Lagrange points after their co-discoverer.



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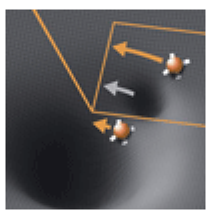
Three points are along the Earth-Moon line: L_1 is between them, L_2 is on the far side of the Moon, and L_3 is on the far side of the Earth. Two other points, L_4 and L_5, are 60 degrees ahead of and behind the Moon in its orbit. Although each represents a special orbit around the Earth, they are called "points" because they appear as fixed locations when viewed in the reference frame that rotates with the orbit of the two massive bodies. Five special spots exist for *every pair of massive bodies* in orbit about each other: the Sun and a planet, a planet and one of its moons, and so on. L_1 and L_2 are of direct interest for understanding the interplanetary transport network, because they form key gateways to faraway destinations.



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The motion of a spacecraft near these points is influenced by a delicate interplay of its velocity with the local gravitational field. The richness of the dynamics makes it possible for a spacecraft to "orbit" L_1 or L_2, even though there is no material object there. Although such orbits around a mere point in space appear very bizarre, they are, in fact, nothing more than near misses to being exactly on L_1 or L_2 and moving at just the right velocity for perfect balance.

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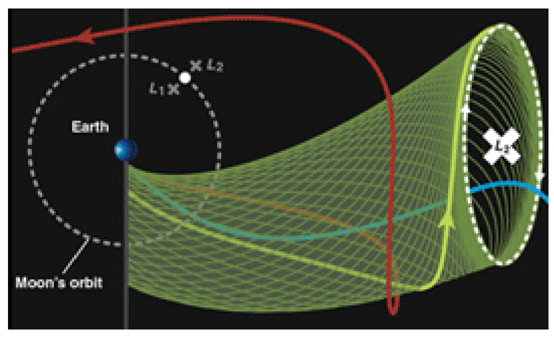
Tubes



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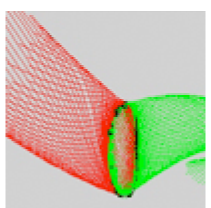
Jen Christiansen (from American Scientist)

The orbits around Lagrange points have tube-shaped surfaces attached to them. For example, a spacecraft given the proper initial velocity can be sent along a trajectory that would then carry it into orbit around, for example, Earth's L_2 point (in the Sun-Earth gravity field). The collection of all similar trajectories forms one *tube* of the interplanetary transport network (green mesh). The important physical property of the tube is that anything that shifts from an orbit that is *around a planet* to an orbit that lies outside must pass along them. A spacecraft on a trajectory inside this tube will pass L_2 and head toward the outer solar system (blue line), whereas one on a trajectory to the outside will fly back toward the Sun (red line). The tube's outer surface is an example of what mathematicians call a stable or unstable manifold *(see box at the lower right)*.

The tube shown is an approaching tube, as it approaches the Lagrange point neighborhood. But all tubes come in approaching and departing pairs.



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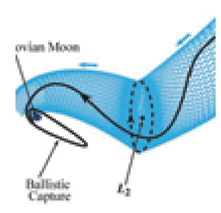
Like water directed by a hose, the set of possible planet-passing objects is imagined to flow along these tubes, but in six dimensions instead of just three. (The tubes "live" in a six dimensional space; three coordinates of position plus three coordinates of velocity. But they are usually shown as projected onto the three-dimensional position space or the two-dimensional orbital plane of the massive bodies.)

It's important to emphasize that tubes exist for Lagrange points throughout the solar system. In the figure at right, a spacecraft inside a tube approaching the L_2 point of one of Jupiter's moons (a.k.a., a Jovian moon) will find itself going from an orbit around Jupiter to an orbit around the moon. The tubes are the mechanism by which ballistic, or unfueled capture, can occur.



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Stable and Unstable Manifolds

The tubes are examples of mathematical objects known as stable and unstable manifolds. The stable manifold of a Lagrange point orbit is the tube approaching the orbit, and is hence "stable" from the point of view of the orbit. Similarly, a departing tube is an "unstable" manifold of the Lagrange point orbit. Well known computer algorithms exist for computing manifolds, which is how the tubes are systematically computed.
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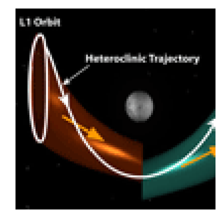
Tube Intersections



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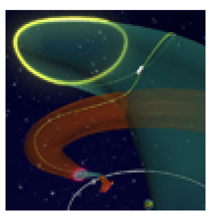
Spacecraft can travel along tubes, but they can also change course onto another tube. A small rocket maneuver will do the trick. But there's a way to do it without using any fuel, using the natural highway interchanges of the interplanetary transport network. The figure at right illustrates a tube intersection near the Moon that occurs between a tube departing an L_1 orbit and a tube approaching an L_2 orbit. A trajectory which goes from one tube to another without using any fuel is called a heteroclinic trajectory, which means it goes from one orbit to another naturally. In practice, to get onto a heteroclinic trajectory, spacecraft usually use some fuel to make small navigation corrections because of our imperfect knowledge of their position and speed.



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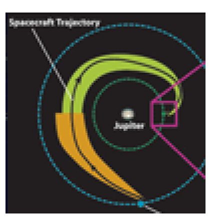
There are also heteroclinic trajectories which connect tubes of two different systems. For instance, at right a heteroclinic trajectory is shown which uses the intersection of a tube departing an L_2 orbit in the Earth-Moon system and a tube approaching an L_2 orbit in the Sun-Earth system. Such a pathway would be useful for a telescope built at a future Lunar L_1 Gateway Station (lower middle) to get to a Sun-Earth Lagrange point orbit where deep space observations could begin. Tube intersections work both ways, so when these a telescope required servicing, it could be returned to the vicinity of the station, again without costing much fuel.

Heteroclinic intersections can seem tricky to find as they involve exact timing: while on the departing tube, you need to be at the right place at the right time (and with the right velocity!) to jump onto an approaching tube. But there are computational ways to find these perfectly timed trajectories, and the results can be spectacular.



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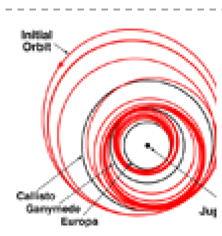
The Jupiter moon system is a good place to test out these ideas since there are four planet-sized moons orbiting Jupiter--Io, Europa, Ganymede, Callisto--just like a mini Solar System. As the moons move at different speeds in their orbits, their tubes are dragged along with them. It's possible to time a spacecraft trajectory so that it jumps from a tube going around one moon to a tube going around another, as shown in the figure.



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Using this tube-hopping approach, a single spacecraft could orbit and explore Jupiter's moons, one after the other, taking a path that uses a technologically feasible amount of fuel. NASA had been considering just such a project, dubbed the Jupiter Icy Moons Orbiter, which would exploit linkages among the tubes of Jupiter and its moons. Without using the tube approach and heteroclinic trajectories, the fuel requirements for such a mission would be prohibitively high, taking it out of the realm of possibility.

Heteroclinic Orbit

In mathematics, in the phase portrait of a dynamical system, a heteroclinic orbit (sometimes called a heteroclinic connection) is a path in phase space which joins two different equilibrium points. learn more...

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People Involved

Dr. Edward Belbruno

Edward Belbruno is a graduate of the Courant Institute of New York University, where his advisor was Juergen Moser. He is a Visiting Research Collaborator in the Department of Astrophysical Sciences, Princeton University. His areas of interest are celestial mechanics. Learn More...

Dr. Martin W. Lo

Since 1986, Martin Lo has been a research scientist in the Navigation and Mission Design Section at the Jet Propulsion Laboratory in Pasadena, California. He received his Bachelor of Science in 1975 from the California Institute of Technology in Mathematics and his PhD. Learn More...

Dr. Josep Masdemont

Josep J. Masdemont is professor in the Applied Mathematics Department of the Technical University of Catalonia (UPC). His research interests include applications of Dynamical Systems and Numerical Analysis to Mission Design. Learn More...

Dr. Shane Ross

Shane D. Ross is on the faculty of Virginia Polytechnic Institute and State University in the Department of Engineering Science and Mechanics. Ross's research interests include the study of spacecraft control and mission design, geometrical methods for engineering systems. Learn More...

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People Involved

Dr. Edward Belbruno

Mathematician, author, and founder of a company dedicated to low energy space travel

Edward Belbruno is a graduate of the Courant Institute of New York University, where his advisor was Juergen Moser. He is a Visiting Research Collaborator in the Department of Astrophysical Sciences, Princeton University. His areas of interest are celestial mechanics, dynamical systems, dynamical astronomy, and aerospace engineering.

He has always loved outer space, and his work led to the first application of chaos theory to space travel--spectacularly demonstrated in 1991 when his calculations rescued a Japanese spacecraft that would have missed the Moon without the assistance of his theoretical work applied to this immediate problem.

Belbruno is president and founder of the company Innovative Orbital Design, Inc. and he holds many international patents on routes in space. He has published numerous papers in the fields of mathematics, aerospace engineering, dynamical astronomy and he has three books in process. Capture Dynamics and Chaotic Motions in Celestial Mechanics is his latest book. He consults regularly with NASA, and recently has appeared on NBC's Today Show twice to discuss space related issues.

He is also a professional artist who has held many one-man shows worldwide, including in Paris, Rome, Turin, Los Angeles, Minneapolis, New York, Boston, and Washington. His oil paintings are in major collections, including NASA headquarters' executive collection in Washington. He loves sports, particularly fixed spin cycling and boxing, which he says keeps him on his toes.

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Space Travel:
Mathematics Uncovers an Interplanetary Superhighway

People Involved

Dr. Martin W. Lo

Former Mission Design and Navigation Manager Jet Propulsion Laboratory, California Institute of Technology

Since 1986, Martin Lo has been a research scientist in the Navigation and Mission Design Section at the Jet Propulsion Laboratory in Pasadena, California. He received his Bachelor of Science in 1975 from the California Institute of Technology in Mathematics and his PhD, also in mathematics, in 1981 from Cornell University.

In 1995 Martin became the Research and Development Software lead for LTool, a high-level interactive, integrated object-orientated mission design programming environment. His work in the area reduced the time for a single Genesis trajectory generation from eight weeks to a few hours.

His most recent research interests include the discovery of the Interplanetary SuperHighway (IPS), a network of ultra-low-energy trajectory conduits generated by Lagrange Points throughout the Solar system. IPS plays a key role in the development of life within the Solar system and provides low energy orbits for many interplanetary missions.

From 1996 to 1999, Martin designed the Genesis Discovery Mission. The Genesis solar panel wind sample return trajectory is one of the most unique and difficult to be flown by JPL in recent years and due to the fact that IPS trajectory requires no deterministic maneuvering after launch, it was the first mission designed with dynamical systems methods. Genesis was launched on August 8th, 2001.

Dr. Martin W. Lo is a member of the Navigation and Mission Design Section at the Jet Propulsion Laboratory, California Institute of Technology. Lo received his PhD from Cornell University (1980) and his BS from the California Institute of Technology in mathematics. As Mission Design Manager, he led the development of the trajectory for the Genesis Mission which launched on August 8, 2001 and is now collecting Solar Wind samples in orbit about L1. He is currently supporting the mission design and technology development of the Terrestrial Planet Finder mission.

He is the organizer of the Lagrange Group, an interdisciplinary and international group of researchers and engineers from universities, NASA centers, and industry whose focus is on the development of nonlinear astrodynamics techniques with applications to space missions and dynamical astronomy. At the request of the NASA Exploration Team, he demonstrated that formation flight in halo orbits is practical for the Terrestrial Planet Finder mission from the trajectory and mission design point of view.

He also conceived of a novel approach for human servicing of libration missions such as the Terrestrial Planet Finder at a Gateway Module in halo orbit about the Lunar L1. This provides a cost effective and efficient approach for human servicing. The spacecraft requiring service may be moved between the Earth libration orbits and the Lunar Gateway module via ultra low energy trajectories in the InterPlanetary Superhighway. This is a vast system of tunnels and passageways in space, discovered by Lo, which connects the whole Solar System and is generated by the Lagrange Points of all of the planets and moons. Not only does the InterPlanetary Superhighway provide low energy orbits for space missions, it is also traveled by comets and asteroids throughout the Solar System. Comet Shoemaker-Levy 9 and the asteroid which killed the dinosaurs both traveled in impact orbits which are similar to the Genesis orbit. Thus the InterPlanetary Superhighway is crucial to the development of life on Earth. Lo believes that the InterPlanetary Superhighway may play a key role in our understanding of low-thrust trajectory design for spacecraft using advanced electric or nuclear propulsion.

He is also leading the development of LTool, JPL's new mission design tool which uses dynamical systems techniques, or "chaos theory" to design highly nonlinear trajectories. His professional interests include mission design, the three body problem, satellite constellation coverage analysis, dynamical astronomy, applied dynamical systems theory, and computational mathematics.

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People Involved

Dr. Josep Masdemont

Professor of Applied Mathematics, Technical University of Catalonia, Spain

Josep J. Masdemont is professor in the Applied Mathematics Department of the Technical University of Catalonia (UPC). His research interests include applications of Dynamical Systems and Numerical Analysis to Mission Design, Formation Flight and Astronomy with special emphasis on Libration Point Orbits for the design of zero-fuel and low-fuel spacecraft trajectories. He has participated in different projects with the European Space Agency (ESA) and NASA/JPL and worked as a consultant for different missions such as SOHO, Herschell-Gaia, WSO, Genesis, TPF and Darwin.

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People Involved

Dr. Shane Ross

Assistant Professor of Engineering Science and Mechanics

Shane D. Ross is on the faculty of Virginia Polytechnic Institute and State University in the Department of Engineering Science and Mechanics. Ross's research interests include the study of spacecraft control and mission design, geometrical methods for engineering systems, and mixing and transport processes. He earned a Ph.D. in control and dynamical systems from the California Institute of Technology in 2004 and was an NSF Mathematical Sciences Postdoctoral Fellow at the University of Southern California.

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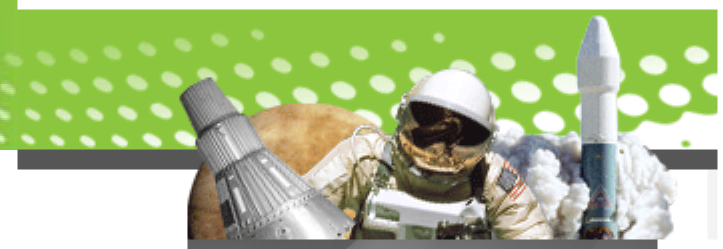

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References and Links

Video Presentation

Watch Shane Ross give a presentation on the interplanetary transport network using RealVideo.
(Broadband, Cable/DSL, 56k Modem)

Magazine Articles

The Interplanetary Transport Network - *American Scientist*

Ride the Celestial Subway - *New Scientist*

Navigating Celestial Currents - *Science News*

Next Exit 0.5 Million Kilometers - *Engineering and Science*

Technical References

Capture dynamics and chaotic motions in celestial mechanics: with applications to the construction of low energy transfers. - *Edward Belbruno 2002*

Dynamical systems, the three-body problem and space mission design. - *Wang Sang Koon, Martin W. Lo, Jerrold E. Marsden and Shane D. Ross, 2007*

New methods in celestial mechanics and mission design. - *Shane D. Ross and Jerrold E. Marsden, Bulletin of the American Mathematical Society, 43:43-73, 2006*

Low energy transit orbits in the restricted three-body problem. - *Charles C. Conley, SIAM J. Appl. Math. 16:732-746, 1968.*

Other Related Links

Math in the Media - *AMS website*

Manifolds in the Genesis mission - *MAA website*

Wikipedia entry

Destination L1

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Mission Design

Previous Mission Trajectories

Possible Future Mission Trajectories

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References and Links