The Lunar L_1 Gateway: Portal to the Stars and Beyond

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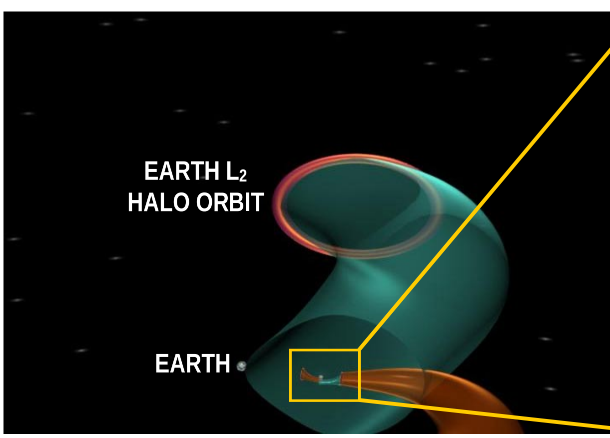
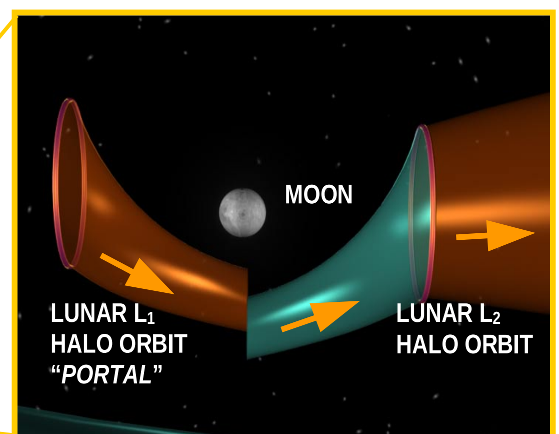
Abstract

Our Solar System is interconnected by a vast system of tunnels winding around the Sun generated by the Lagrange Points of all the planets and their moons. These passageways are identified by portals around L_1 and L_2, the halo orbits. By passing through a halo orbit portal, one enters this ancient and colossal labyrinth of the Sun. This natural Interplanetary Superhighway System (IPS, see Figure 1) provides ultra-low energy transport throughout the Earth's Neighborhood, the region between Earth's L_1 and L_2. This is enabled by a coincidence: the current energy levels of the Earth L_1 and L_2 Lagrange points differ from that of the Earth-Moon by only about 50 m/s (as measured by ΔV). The significance of this happy coincidence to the development of space cannot be overstated. For example, this implies that lunar L_1 halo orbits are connected to halo orbits around Earth's L_1 or L_2 via low energy pathways. Many of NASA's future space observatories located around the Earth's L_1 or L_2 may be built in a lunar L_1 orbit and conveyed to the final destination via IPS with minimal propulsion requirements. Similarly, when the spacecraft or instruments require servicing, they may be returned from Earth libration orbits to the Lunar L_1 orbit where human servicing may be performed. Since the lunar L_1 orbit may be reached from Earth in less than a week, the infrastructure and complexity of long-term space travel is greatly mitigated. The same orbit could reach any point on the surface of the Moon within hours, thus this portal is also a perfect location for the return of human presence on the Moon. The lunar L_1 orbit is also an excellent point of departure for interplanetary flight where several lunar and Earth encounters may be added to further reduce the launch cost and open up the launch period. The lunar L_1 is a versatile hub for a space transportation system of the future.



a.



b.

Figure 1.a. Artist's conception of portions of the Interplanetary Superhighway (tubes) of the Sun-Earth-Moon System generated by the halo orbits. The green tubes approach the halo orbits, the red tubes go away from the halo orbits. Thus, the halo orbits are the literal "Highway Interchanges" of the Interplanetary Superhighway. 1.b. An exploded view of the Lunar portion of the Interplanetary Superhighway. Arrows indicate the direction of transport.

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1. Human Servicing of Libration Missions from the Lunar L_1

The Space Telescope is one of NASA's most popular and successful missions. Not a week goes by but our imagination is captivated by some new exciting images of distant galaxies or nebulae observed by the Space Telescope. But, all this would not be possible without regular servicing of the Space Telescope by the astronauts via the Space Shuttle. In view of this experience, as NASA continues to build space observatories at different wavelengths and for different purposes, the role of human servicing of these complex and expensive observatories is a crucial element which must be carefully considered.

In recent years, halo orbits around the Earth's Lagrange Point (EL_1, EL_2, see Figure 2) have become a popular location for space missions. NASA has a lot of experience with halo orbit missions. In 2001 alone NASA is sending two missions to orbit the Earth's Lagrange points: MAP is well on its way to EL_2 as is Genesis to EL_1 (Figure 3 provides the Genesis orbit, see Lo et al [1]). The Next Generation Space Telescope and the Terrestrial Planet Finder mission (TPF) are both considering using EL_2 orbits. The constant cold environment of EL_2 is well suited to observatories with detectors requiring low temperatures for operation. Communications geometry from EL_2 to the Earth is nearly constant with the range at roughly 1.5 million km from the Earth. Furthermore, it requires a ΔV of only 3200 m/s to insert into typical halo orbits from a 200 km parking orbit around the Earth. In general, operations cost is low: only four to six maneuvers per year are required for station keeping with a total ΔV budget less than 5 m/s per year. Another example is the Genesis trajectory which is completely ballistic; if everything is perfect with no errors and infinite precision, the Genesis trajectory requires no deterministic maneuvers from launch to Earth Return at the Utah Test and Training Range. All of the maneuvers in the Genesis Mission are used to accommodate spacecraft, instrument, and operational issues in addition to the statistical navigation and station keeping maneuvers. Otherwise, no deterministic maneuver is needed dynamically.

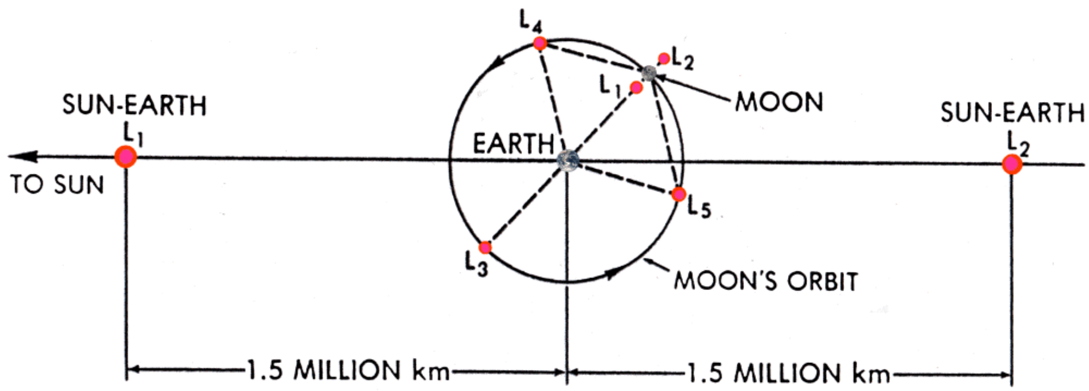


Figure 2. Schematic diagram of the Lagrange Points of the Earth-Moon, and Sun-Earth Systems.

In the last few years, NASA planners have seriously considered providing human servicing to libration missions (see Condon [2]). The problem is that, the 3200 m/s transfer to orbits around the Lagrange points require approximately 3 months of travel time. With transfer orbits to EL_2 well outside of the Earth's magnetic field, such a voyage would in principle be not very different from one going to Mars. To reduce the transfer time in any significant manner (down to one day) requires an increase of the transfer ΔV by roughly an order of magnitude. The infrastructure cost and risk for both options are extremely high. At the 2000 Lagrange Points and the Exploration of Space Workshop in Pasadena, CA. [3], Lo suggested an alternate approach by using the Moon's L_1 (Lunar L_1: LL_1) as a base of operations for servicing missions at the Earth's Lagrange points.

By placing a Lunar Gateway Habitat in orbit around LL_1, the spacecraft at EL_2 can be brought back and forth to LL_1 with relatively little cost. The point design trajectory presented in this paper requires only a single 14 m/s deterministic maneuver (statistical maneuvers not included) to convey a spacecraft from LL_1 to EL_2 orbit (see Figure 4). Transfers for EL_2 to LL_1 would have similar costs. With optimization, even this small deterministic maneuver may be removed in some instances. The transfer from the LL_1 to EL_2 region requires about 40 days. This efficient transfer is achieved by dynamical channels in the "Interplanetary

Superhighway" (IPS) generated by the Sun-Earth-Moon system described in the next section. For rendezvous missions, the transfer time will be of the order of months which may be shortened by additional maneuvers.

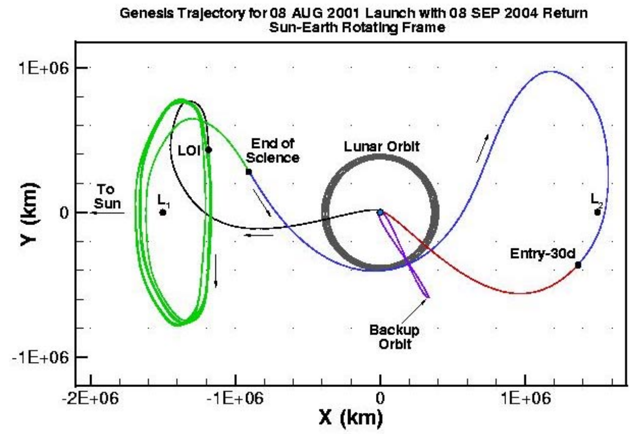


Figure 3. The Genesis orbit. Genesis will remain in an L_1 halo orbit for about 5 orbits (2.5 years) to collect solar wind samples and return them to Earth. The excursion to L_2 is needed to achieve a day-side entry at the Utah Test and Training Range to facilitate the final parachute deployment with mid-air retrieval by a helicopter.

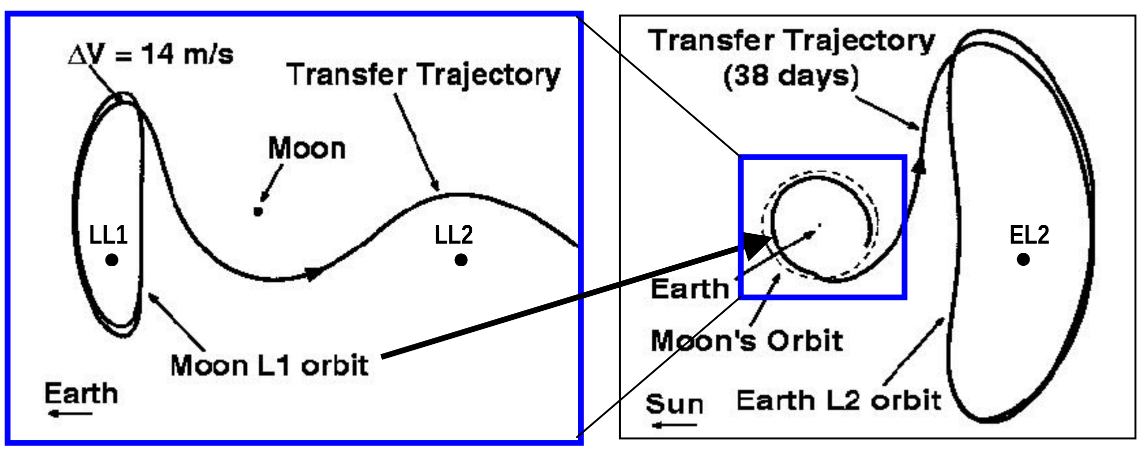


Figure 4. Transfers between planar Lyapunov orbits around Lunar L_1 and Earth L_2. 3a. The Lyapunov orbit around the Lunar LL_1 and the 14 m/s maneuver to get onto the transfer orbit. 3b. The transfer orbit going from the Moon to the Earth's EL_2.

Lunar L_1 is an ideal and logical next step for extended human presence in space beyond LEO (Low Earth Orbit). To first order, from energy considerations, it requires only a ΔV of 3150 m/s to reach LL_1 from a 200 km parking orbit around Earth. Although, this will vary depending on the transfer time. In the worst case, it is bounded above by transfers to the Moon. We are currently studying this issue. Station keeping is required once or twice a week with a total ΔV budget of around 10 m/s per year (Howell et al[4]). However, advances in navigation technology in the next decade may provide a completely autonomous system for station keeping with even lower cost. Communications is relatively simple, since LL_1 is close by and always in view of the Earth. And, of course, NASA has a tremendous amount of experience with human missions to the Moon. This fact alone greatly reduces the risk of this approach.

These facts combine to suggest that a halo orbit around LL_1 provides an ideal location for a "service station" or a "hub" for missions in Earth libration orbits. Moreover, as shown in Paffenroth, Doedel, and Dichmann [5], there are large families of orbits with similar characteristics to halo orbits in the Earth's Neighborhood (the region between EL_1 and EL_2) which will be useful for future missions. Spacecraft in these orbits may also be serviced by the LL_1 Gateway. Beyond the Earth's Neighborhood, LL_1 can also serve as a point of departure for missions with destinations ranging from Mercury to the Kuiper Belt and beyond. By taking advantage of the dynamics of the IPS of the Sun-Earth-Moon system, launches from the LL_1 Gateway can effectively increase the narrow launch periods of interplanetary missions from a few days to weeks and months. This is achieved by launching earlier and spending the extra time in the Earth's Neighborhood until a final Earth flyby with injection onto the desired interplanetary transfer orbit. During the time in the Earth's Neighborhood, additional lunar and Earth flybys can further increase the energy of the spacecraft. Halo orbits near LL_1 can truly be portals to the Solar System and beyond.

2. The Interplanetary Superhighway (IPS)

In the previous section, it was noted that a ΔV of 3200 m/s is required to reach an Earth L_2 orbit, and a ΔV of 3150 m/s is required to reach the Lunar L_1 point, both from a 200 km parking orbit around the Earth. The fact that these two orbital regimes differ by a mere 50 m/s is remarkable and hints that something wonderful is happening there. What this tells us is that the energy of halo orbits around EL_2 and the energy of halo orbits around LL_1 are very close. The proximity of the energy surfaces of EL_2 and LL_1 is what provides the low-energy transfers between them. What exactly is the mechanism for this low energy transfer? Does this exists elsewhere? The mechanism is the "Interplanetary Superhighway" which exists throughout the Solar System (see Figure 1).

In fact, our Solar System is interconnected by a vast system of winding tunnels in space around the Sun and planets which we call the "Interplanetary Superhighway" or IPS for short (Lo, Ross, [6]). The IPS is generated by the Lagrange points of all the planets and satellites within the Solar System. For every three body system (such as the Sun-Planet-Spacecraft system), there are five Lagrange Points. These points are special locations in space where the gravitational forces and the rotational forces within the Three Body System are balanced. They were discovered by Euler (L_1, L_2, L_3) and Lagrange (L_4, L_5). Figure 2 shows schematically the Lagrange points of the Earth-Moon System and their geometric relationship with the Sun-Earth's L_1 and L_2 Lagrange points. Figure 1 provides an artist conception of a portion of the IPS in the Earth's Neighborhood connecting the Lunar L_1 Gateway with missions in orbit about Earth's L_2. Figure 5 shows an actual computation of a portion of the IPS which provides low energy transfers from low Earth orbit to a halo orbit at EL_2 for the TPF mission [17]. For an exposition on the dynamics of the Lagrange points and the foundations of the IPS, see Koon, Lo, Marsden, and Ross, [7] and references therein.

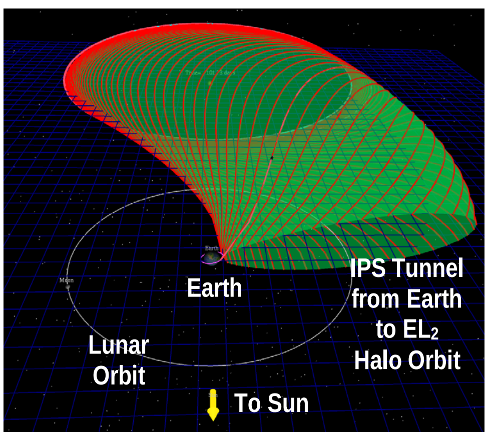


Figure 5. The Interplanetary Superhighway tunnel which provides a low energy transfer from Earth to a halo orbit at EL_2 (at the end of the tunnel) for the TPF mission [17].

2.1 The Geometric Structure of the IPS

Where does the tunnel in Figure 5 come from? The surface of the tunnel is generated by all the trajectories that asymptotically wind onto the halo orbit without any maneuvers. This tube-like surface is called the stable manifold in Dynamical Systems Theory, a branch of mathematics studying the global behavior of differential equations. Dynamical Systems Theory is more popularly known as “Chaos Theory” from the discovery of “deterministic chaos” in the solutions of ordinary differential equations. Similarly, there is a set of trajectories which asymptotically wind off of the halo orbit without any maneuvers. This tunnel is called the unstable manifold. In Figure 6b, we show the typical tunnel structures generated by a periodic orbit around L_1 and L_2. Figure 6a shows a schematic diagram of the Earth’s global IPS at a particular energy level, E. Compare with Figure 1 to see the 3-dimensionality of the tunnels.

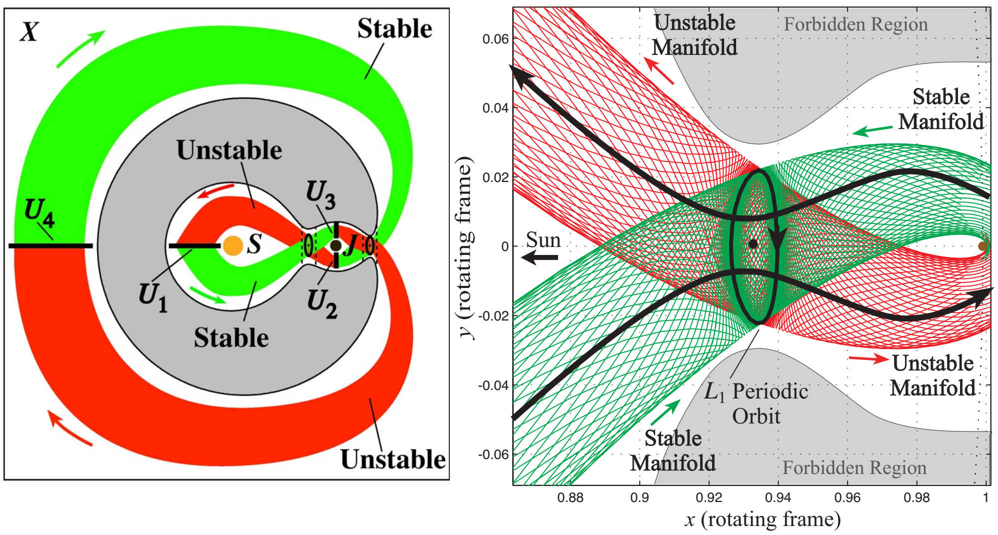


Figure 6.a. The schematic diagram of the Earth’s global Interplanetary Superhighway at a particular energy level, E. The green tunnels wind onto the periodic orbit at L_1 or L_2. The red tunnels go away from the periodic orbit at L_1 or L_2. These tunnels are 3 dimensional and are projected onto the Ecliptic. The gray region in a horseshoe shape is inaccessible to particles in the Sun-Earth system at the energy level E. 6.b. The detailed typical tunnel structures generated by a periodic orbit around L_1. The periodic orbit can be a Lyapunov orbit, a halo orbit, or other unstable periodic orbits around the Lagrange points.

The periodic orbit (there are other types besides halo orbits) which generates the tunnels are truly the “portals” to this system of tunnels. To see this, let us select a tunnel system at the energy level E as in Figure 6 and examine transport within this system. Let us assume the planet here is the Earth. Note the three marked regions: S, J, X. S is the Sun Region inside the orbit of Earth. J is the Earth Region between L_1 and L_2. X is the Exterior Region, outside the orbit of Earth. Recall the gray horseshoe region is the Forbidden Region where particles with energy E cannot reach. In order for a particle at energy E to enter or exit the J Region, it must pass through the periodic orbit at L_1 or L_2. For the planar case, where we assume all particles move only in the XY-plane (the Ecliptic here), there is a theorem guaranteeing this rule of transport (see Conely [8] and McGehee [9]). In the 3 dimensional case, recent results show a much more complex picture, but essentially the same as in the 2 dimensional case (see Gomez, Koon, Lo, Marsden, Masdemont, Ross [10]). Thus, in a very real sense, the periodic orbits act like portals to the J Region controlling all who pass through this region. At the same time, the neighborhood surrounding the periodic orbits are the “Freeway Interchange” of the Interplanetary Superhighway. Because, it is here that one can select which of the four tunnels connected to the periodic orbit for travel (see Figure 6.b). In Koon, Lo, Marsden, Ross [7], it is shown that the entire system of tunnels generated by the periodic orbits is chaotic. In other words, the tunnels generate determinisitic chaos. This means that for very little energy, one can radically change trajectories that are initially close by. In Figure 7, we show a small portion of the surface of the tube of trajectories leaving the Genesis halo orbit which generates the Earth-Return trajectory. The effects of the Moon are evident. One can imagine from this plot that the tunnel becomes highly distorted and broken up as it goes around the Earth's Neighborhood. Part of it escapes the Earth's Neighborhood via the L_2 portal which is invisible here. Part of it is captured by the Earth-Moon system. If one looked carefully, one can even see the trajectory with a lunar flyby. Finally, some of it will escape via the L_1 halo orbit eventually.

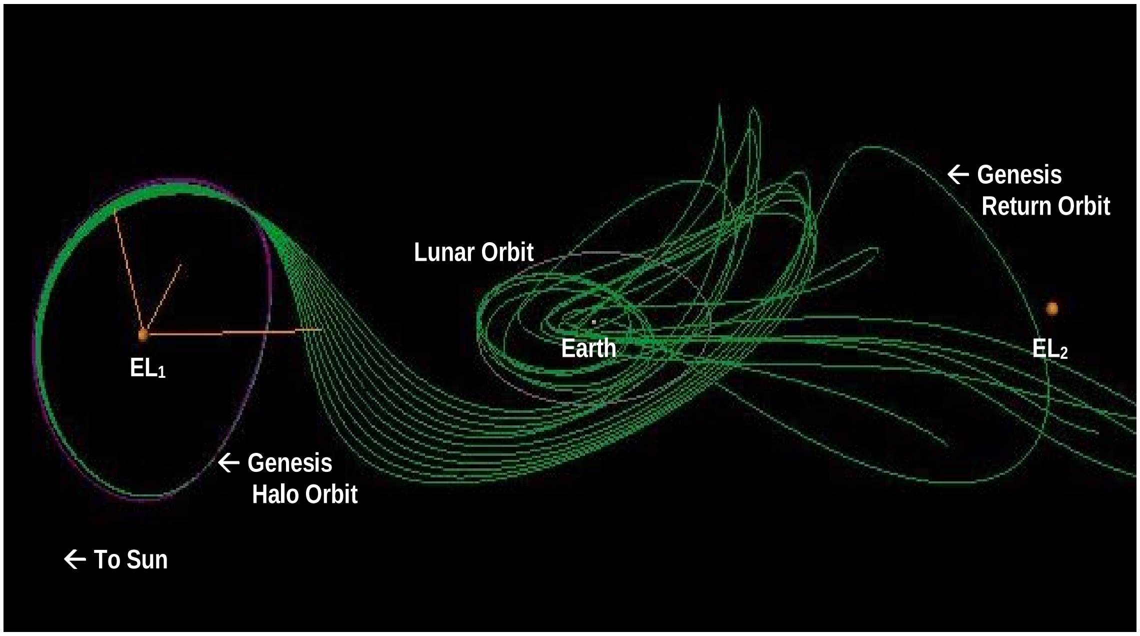


Figure 7. Portions of the surface of the unstable manifold of the Genesis halo orbit. This is part of the Interplanetary Superhighway in the Earth's Neighborhood which leads away from the Genesis halo orbit for a return orbit to Earth as noted in the diagram.

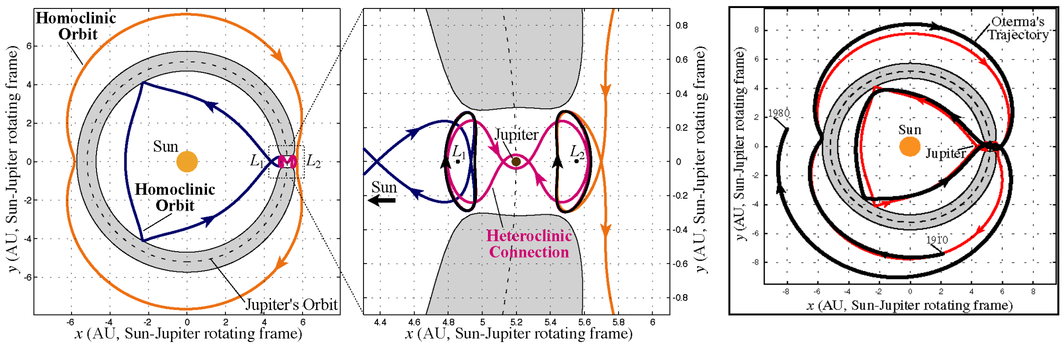
3. Some Examples of IPS Application to Solar System Dyanmics and Space Missions

In this section, we examine the IPS and some of the salient applications to Solar System dynamics as well as space missions. The two key ideas are:

I. IPS provides a new lens through which we can understand the dynamical behavior of the Solar System.
II. Understanding the IPS and mimicking the behaviors of natural bodies such as comets and asteroid under IPS control can provide valuable insight and techniques for designing innovative low-energy missions.

In Figure 8.a, we exhibit a system of pathways linking the S, J, X regions of Jupiter with two periodic orbits around Jupiter's L_1 and L_2. This chain of orbits is called a homoclinic-hetroclinic chain and is an important pathway within the Jovian IPS. In Figure 8.b we have superimposed comet Oterma's path over the chain. Note the remarkable resemblance between the comet's path and the chain. This suggests that comets closely shadow such paths within the IPS. Howell, Marchand and Lo [11] examined the motions of Helin-Roman-Crockett more closely by matching the pieces of Jupiter's IPS tunnels with the comet orbit shadowing them. This confirms the initial observations of Lo and Ross [6] that the temporary capture phenomenon of Jupiter comets is controlled by Jupiter's IPS generated by its Lagrange points. In fact, the Shoemaker-Levy 9 comet followed precisely the Jovian IPS to its spectacular final demise crashing into Jupiter. Similarly, the Genesis Trajectory is really an Earth impact trajectory that Near Earth Asteroids and Comets can follow, leading to similar impacts. It is estimated about 1% of the Near Earth Objects fall into this category and are considered the most dangerous because they have orbits that naturally lead to Earth impact (Valsecchi, [12]) like the Genesis orbit. Michael Mueller (author of the Nemisis Star theory) and

Walter Alvarez [13] noted that there is evidence that the asteroid which impacted the Earth and wiped out the dinosaurs may have followed a Genesis-like orbit.



a. b.

Figure 8.a. A homoclinic-heteroclinic chain within the Jovian system. These are a special set of trajectories linking the S, J, X regions of Jupiter via two of its periodic orbits at L_1 and L_2. 8.b. The orbit of comet Oterma superimposed on the chain showing how closely the comet orbit is guided by the chain.

But instead of doomsday, through a series of well chosen maneuvers one may be able to capture such a rogue asteroid or comet in the Earth-Moon system and tame it for an almost infinite supply of precious resources! In Koon, Lo, Marsden, and Ross [14], it is shown how ballistic lunar captures may be achieved using the IPS. This, of course, uses exactly the same dynamical mechanism for the temporary capture of Jupiter comets. In this dynamical regime, finesse is the key.

Seeing such a complex array of chaotic behavior, one is tempted to despair. But just the opposite is true. This complex jumble can be analyzed and classified with the utmost precision using modern mathematical and computational methods. Furthermore, the existence of deterministic chaos is the source of "Low Energy Transport" within the Solar System. It is precisely deterministic chaos which permitted the design of a completely ballistic trajectory for the Genesis Mission mentioned earlier. Koon, Lo, Marsden, and Ross [7] provides one of the classifying theorems. It states that given any positive integers N_S, N_1, N_J, N_2, N_X, there exists a natural orbit which winds around the Sun for N_S revolutions in the S Region, winds around L_1 for N_1 revolutions, winds around the Earth for N_J revolutions, winds around L_2 for N_2 revolutions, and winds around the X Region for N_X revolutions. In fact, for an infinite sequence of such integers going between the S, J, X regions, such a natural orbit exists. Hence comets like Oterma, Gehrels3, Helin-Roman-Crockett, or Shoemaker-Levy9 are simply following the recipe given by this theorem.

We close this section by remarking that the Interplanetary Superhighway play an important role in the control of the motions of the Asteroid Belt, the Kuiper Belt, the planetary rings, the giant zodiacal dust tori. The transport within the Solar System and its effects on the morphology of structures within the Solar System are governed to a great extent by the Interplanetary Superhighway. The picture we should keep in mind as we leave this section is that the Solar System is dynamic and connected from the Kuiper Belt to the center of the Sun by this invisible, complex system of tunnels and pathways, orbiting and intersecting one another like the gears within a clock. Instead of planets orbiting the Sun in isolated Keplerian orbits, the Solar System is an integrated entity, whole and organic, constantly evolving with materials moving in and out of the system via the Interplanetary Superhighway.

4. Conclusions and Future Work

The Interplanetary Superhighway provides new classes of ultra-low energy trajectories for space missions by exploiting the three body dynamics of the Solar System. Moreover, these nonlinear trajectories are highly malleable and provide important new opportunities for the exploration and development of space. Already for missions like Genesis, and for Programs like the Earth's Neighborhood, ideas and concepts derived from the Interplanetary Superhighway have been crucial in enabling these missions and Programs. And as mentioned earlier, Paffenroth et al [5] showed that we have just barely scratched the surface of orbital possibilities within the Earth's Neighborhood alone. So far, we have only examined the IPS tunnels and pathways generated by a few of the orbital classes around the Lagrange points. The orbits presented by Paffenroth et al [5] provide entirely new classes with different characteristics and utility which must be carefully analyzed and developed. A simple measure of the aerospace community's general consensus of the usefulness of the IPS may be provided by the fact that there were two full sessions devoted to libration missions at the recent Astrodynamics Specialist Conference (Quebec City, July 30 to August 2, 2001). Just five years ago, there might have been one or two papers on the subject at such a conference.

The Interplanetary Superhighway represents not only new trajectory possibilities, but a new methodology for the development of trajectories and space missions. This methodology is by no means unique to the mission design community, but is a phenomenon in the broader scientific and engineering community. Generally speaking, in the last fifty years, the mathematical methods used by the applied and engineering community have been mostly limited to methods developed in the 18th and 19th century. Modern mathematics have not played a more significant role not only because the mathematical formalism was inaccessible to non-experts, but more importantly, there were no computational tools. Today, modern computers and computational mathematics have reached the point where many of the former strictly theoretical subjects have now become useful engineering tools simply because numerical computation is now possible. The tunnels of the Interplanetary Superhighway are a perfect example. Mathematically, they are called invariant manifolds and were identified by Poincaré in his celebrated study of the three body problem in the late 19th century [16]. But, it is the fact that we now are able to compute these theoretical objects which allows us to use it for space mission design. A casual search through journals in any scientific or engineering discipline will reveal a similar picture. Thus the development of the Interplanetary Superhighway has far reaching consequences aside from providing new trajectory options. The methods behind it provide a new, integrative, and multidisciplinary approach to solving practical engineering problems in space mission design. The applications span the range of NASA Programs. We cite a few examples from the aforementioned AAS Conference in Quebec City: sample return to Earth (Barden et al [17]), human servicing of space missions beyond LEO (Condon et al [2]), new orbits in the Earth-Moon system (Paffenroth et al [5]) formation flight for interferrometry (Gomez et al [18]), a tour of the Jovian satellites (Koon et al [14]), etc.

Having said this, it should be noted that the development of the Interplanetary Superhighway for space missions is itself still in infancy. It is as if we have just discovered that there are great currents within the oceans, or that there is such a thing as jet streams in the atmosphere. But, we have no charts to show us where they lie, where they go to, what is their extent, what are their limitations, how they connect with one another, how to get in and out of them, how to switch from one stream into another, perhaps our ships may not be equipped to take advantage of these strong currents. And so on goes the analogy.

The development of the Interplanetary Superhighway in no way invalidates current methods. For example, the discovery of the rational numbers in no way replaced the utility of integers. It simply enlarged our set of tools. Each technique has its own use and its own place. The Interplanetary Superhighway is not the final word either. Beyond the rationals, there are irrational numbers which are more numerous than the rationals. Beyond that, there are imaginary numbers. What is needed is to enlarge our tools kits and computational infrastructure to enable us to work with trajectories combining segments from both the Interplanetary Superhighway and conic orbits. Going back to the number system analogy: our abacus has served us well with integer arithmetic, but now we need a calculator which can handle both integer and rational numbers.

We now possess the fundamental tools and technologies to systematically explore and develop the Interplanetary Superhighway for space applications. We need to map out their full extent throughout the Solar System. Like the Digital Sky Survey, or the Human Genome Project, we need to have a Solar System Mapping Project to identify and catalogue the full extent of the Interplanetary Superhighway so that one day in the near future we may have a scene like the following. You are at the Hertz Rent a Spaceship counter in the Ganymede L_2 Gateway Hub. You want to visit Io's volcanoes. The robot attendant directs your attention to the Holographic Trip Planner provided by the Space Division of the AAA. A series of options are provided and after making your selections, a final holographic Triptik is generated and communicated to your vehicle. And off you go to IO via the Jovian Interplanetary Superhighway, with a stop at Europa to view its oceans.

But, for now, perhaps we can build the Lunar L_1 Gateway Hub and explore our own Earth's Neighborhood.

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