The Lunar L_1 Gateway: Portal to the Planets

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- **And the work of many others: H. Poincare, J. Moser, C. Conley, R. McGehee, R. Farquhar, J. Llibre, R. Martinez, C. Simo, S. Wiggins**

Themes

- ***Transport in the Solar System Via the InterPlanetary Superhighway (IPS)***
  - **Three Body Problem**
  - **Material Transport in Celestial Mechanics**
  - **Applications to Space Mission Design**
- ***Lunar L1 Gateway Station***
  - **Low cost to many destinations**
  - **Transportation hub**
  - **Construction & repair facility**
  - **Possible commercial uses**

Why Study Transport Via the IPS?

- ***Planetary Science***
  - **Transport of material between planets**
  - **Comet, asteroid impacts**
- ***Extend Human Presence in Space***
  - **Low energy transport to/from gateway stations**
  - **Capture and mining of near-Earth asteroids**

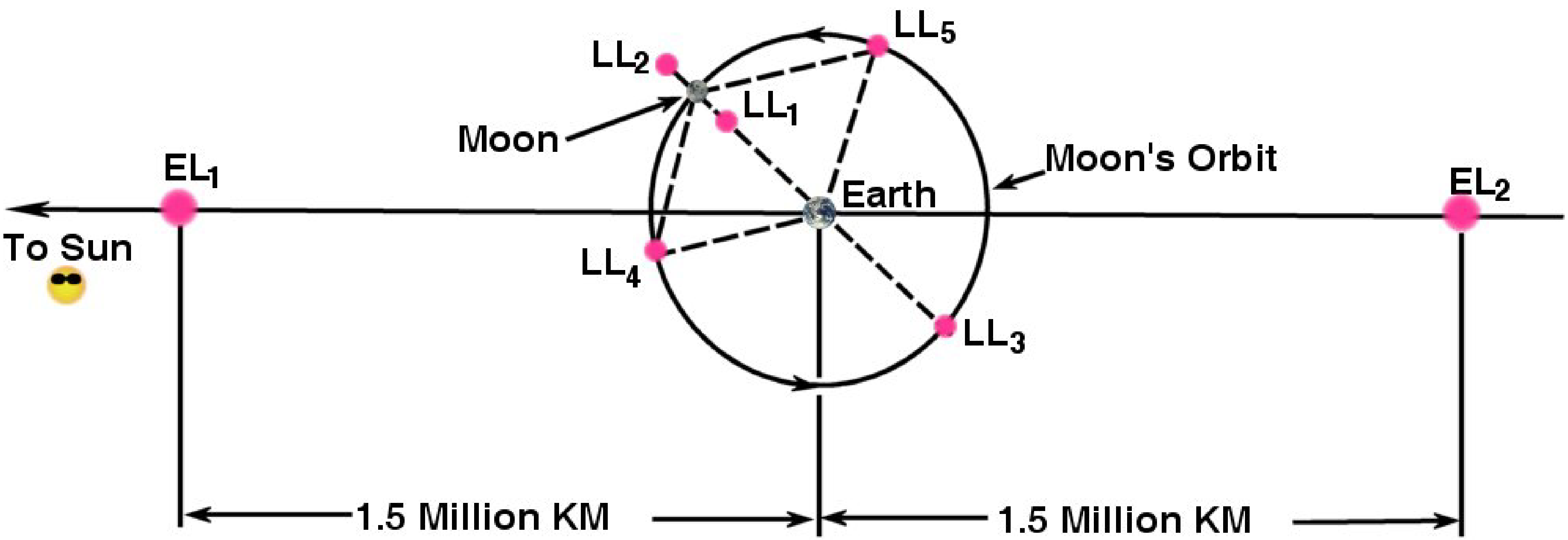
Outline

- ***The InterPlanetary Superhighway***
  - **Tubes connecting the solar system**
- ***Transport in the Solar System***
  - **eg, Jupiter comets**
- ***New Mission Concepts***
  - **Petit Grand Tour of Jovian moons**
  - **Lunar L_1 Gateway station**
    - **Human servicing of libration missions from lunar L_1**
    - **Potential commercial uses**
  - **Rendezvous with Mars, A Human Mission**

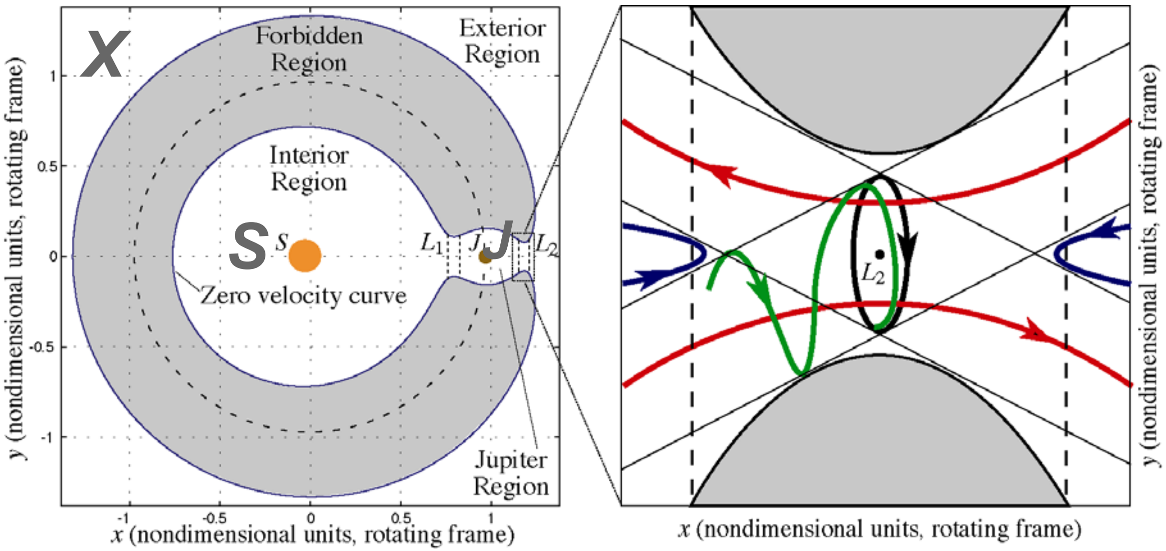
Halo Orbit Transfer and Insertion Via The InterPlanetary Superhighway

Lagrange Points in Near-Earth Space

- ***Every 3 Body System Has 5 Lagrange Points***
  - **Earth-Moon-S/C: LL_1, LL_2, ... LL_5**
  - **Sun-Earth-S/C: EL_1, EL_2, ...**
  - **Generate the InterPlanetary Superhighway near Earth**



Orbital Zoology Near Lagrange Points



S: Sun Region

J: Jupiter Region

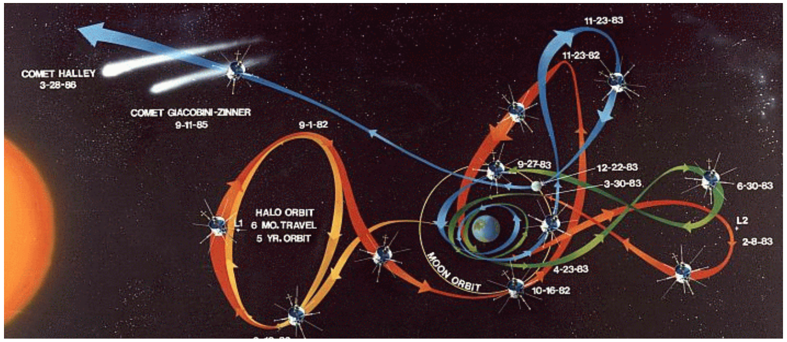
X: Exterior Region

(Outside Jupiter's Orbit)

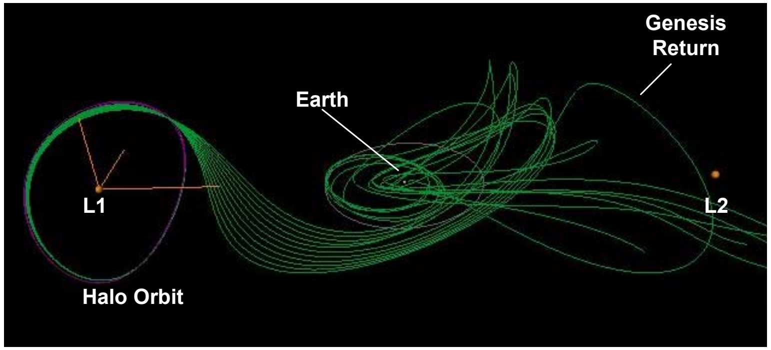
- ***Four Families of Orbits (Conley [1968], McGehee [1969])***
  - **Periodic Orbit (Planar Lyapunov)**
  - **Spiral Asymptotic Orbit (Stable Manifold Pictured)**
  - **Transit Orbits (*MUST PASS THRU PERIODIC ORBIT*)**
  - **Non-Transit Orbits (May Transit After Several Revolutions)**

Why Dynamical Systems Theory?

- **Traditional Approach**
  - **Requires First Hand Numerical Knowledge of Phase Space**
  - **Each Trajectory Must Be Computed Manually By Hand (Slow)**
  - **Optimization Nearly Impossible**
- **Dynamical Systems Provides Theory**
  - **Software: Automatic Generation of Trajectories**
  - **Software: Automatically Maps Out Phase Space Structures**
  - **Near Optimum Trajectory**
  - **Automated Parametric Studies & Monte Carlo Simulations**



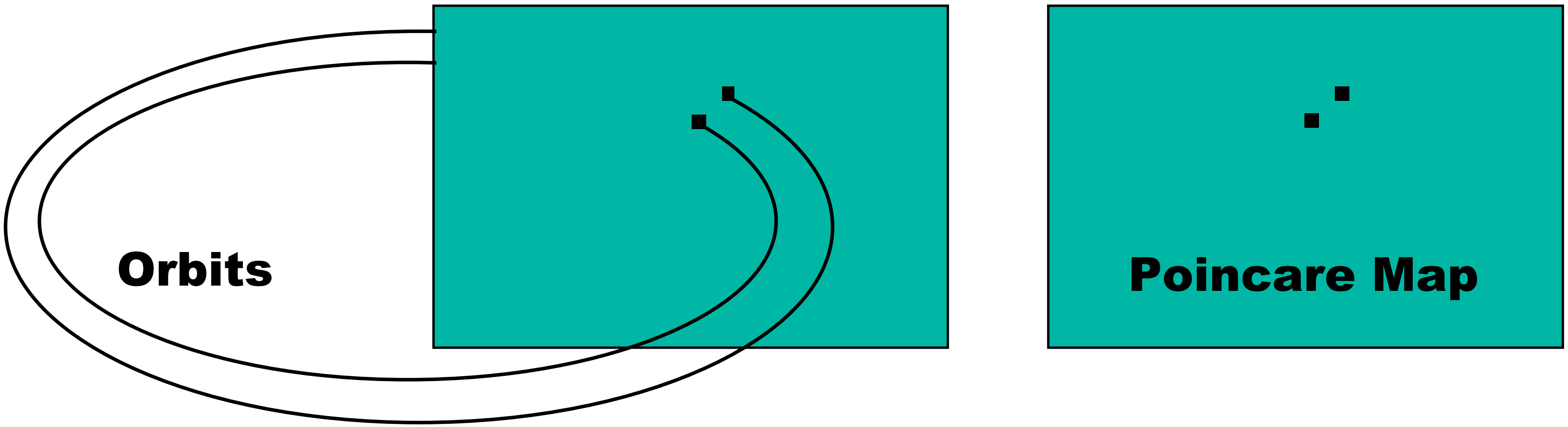
ISEE3/ICE Orbit



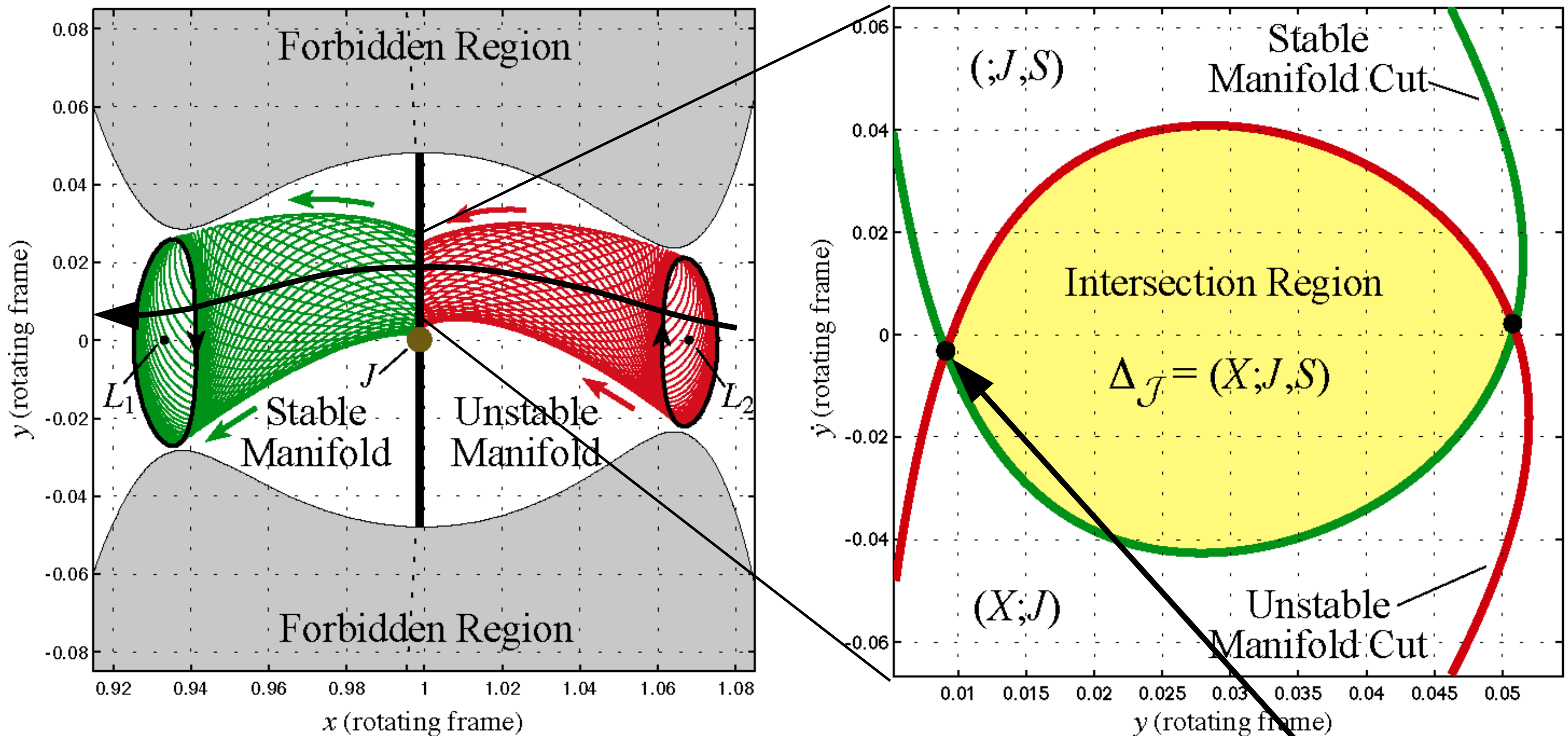
Genesis Unstable Manifold

Using Poincare Sections

- Invariant Manifold Structures in High Dimensions (>3)
- Cross Sections (Poincare) Reduce the Dimensions by 1
  - Periodic Orbits Become Finite Number of Points
  - Chaotic Orbits Cover Large Portions of Phase Space
  - Reveals Resonance Structure of Phase Space

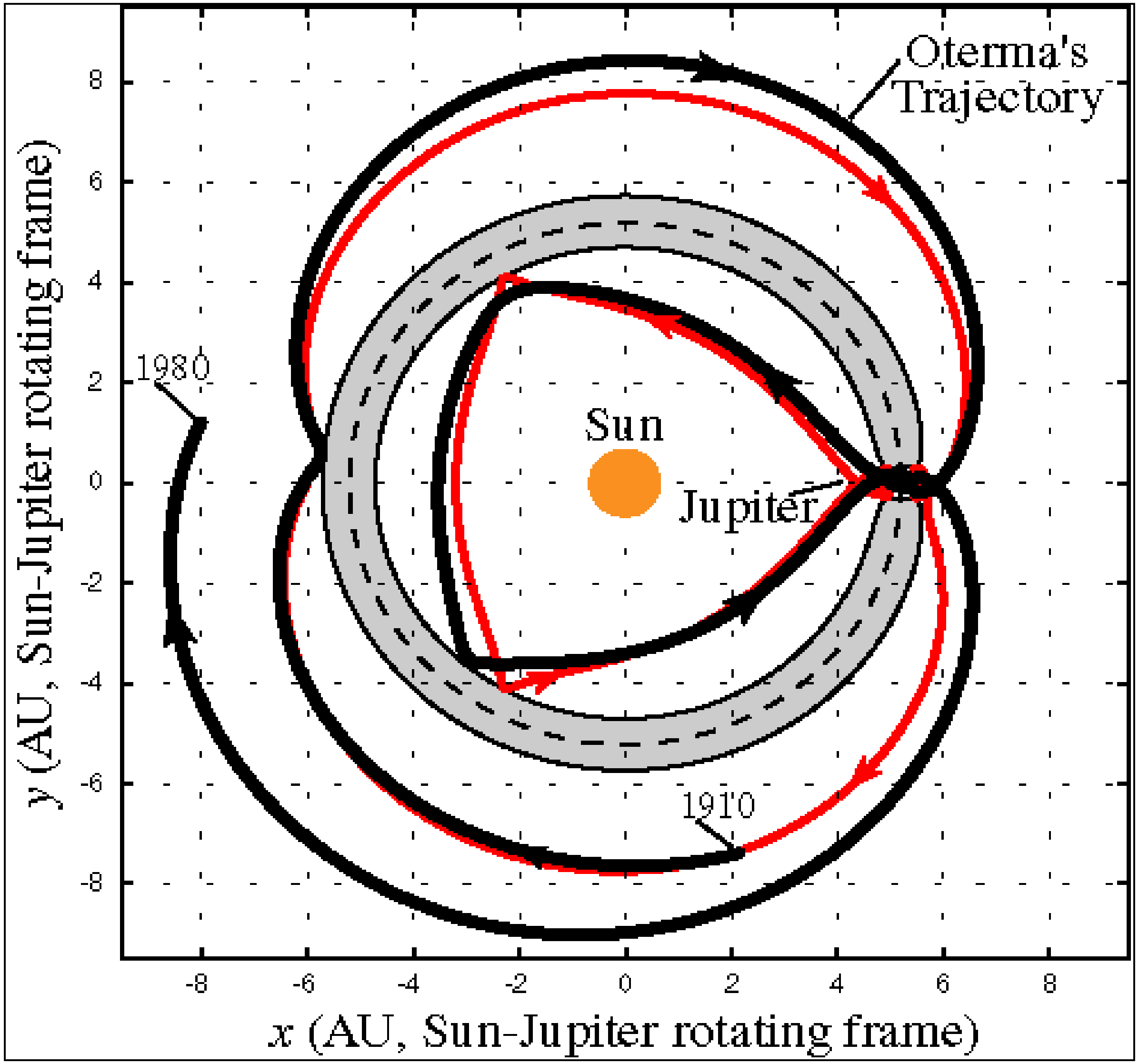


Tunneling Through Phase Space



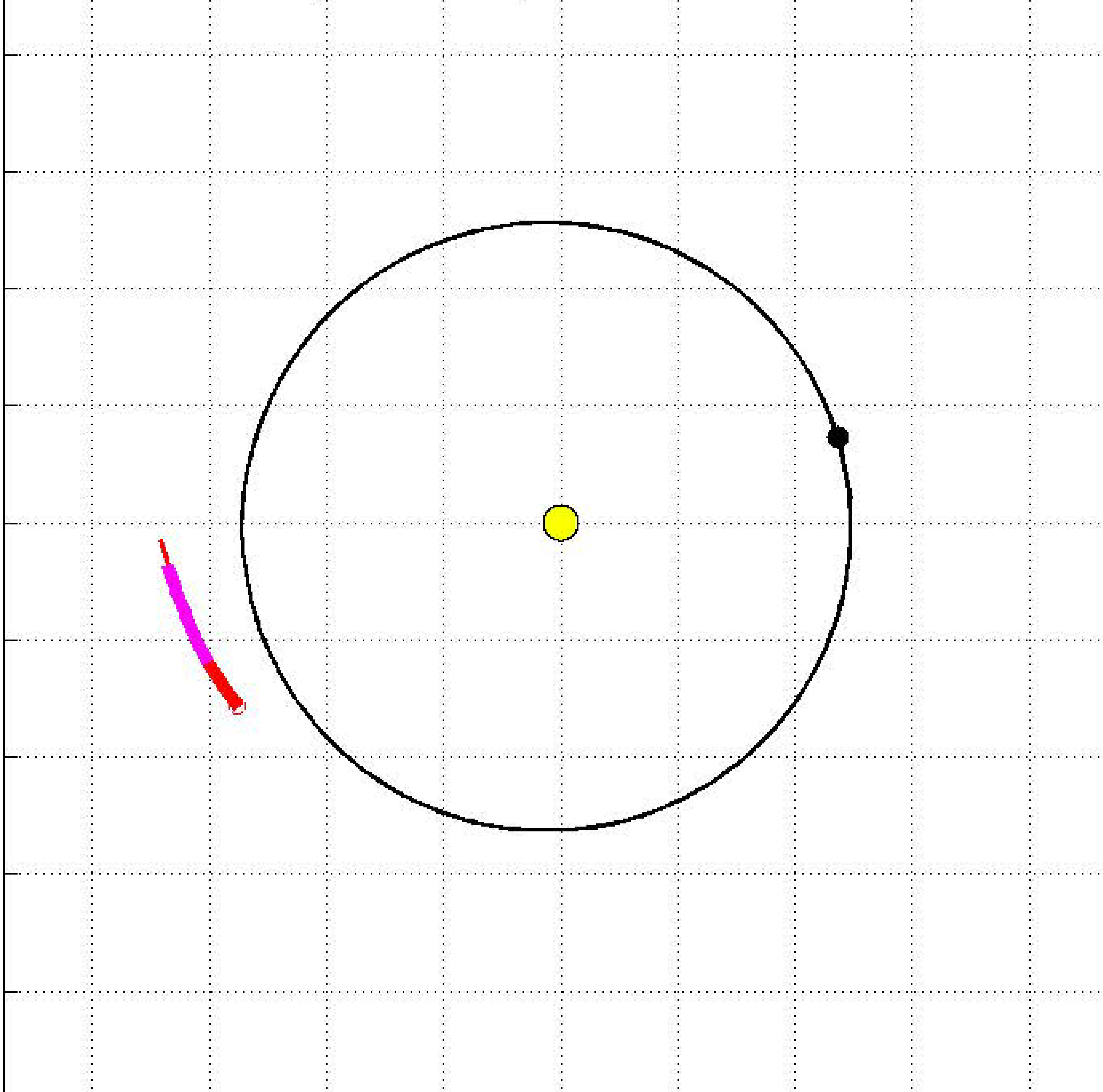
- **Cross Section of Tube Intersection Partitions Global Behavior**
  - **Yellow Region Tunnels Through from X Through J to S Regions**
  - **Green Circle: J to S Region, Red Circle: X to J Region**
  - **Genesis-Type Trajectory Between L_2 and L_1 Halo Orbits (Heteroclinic)**

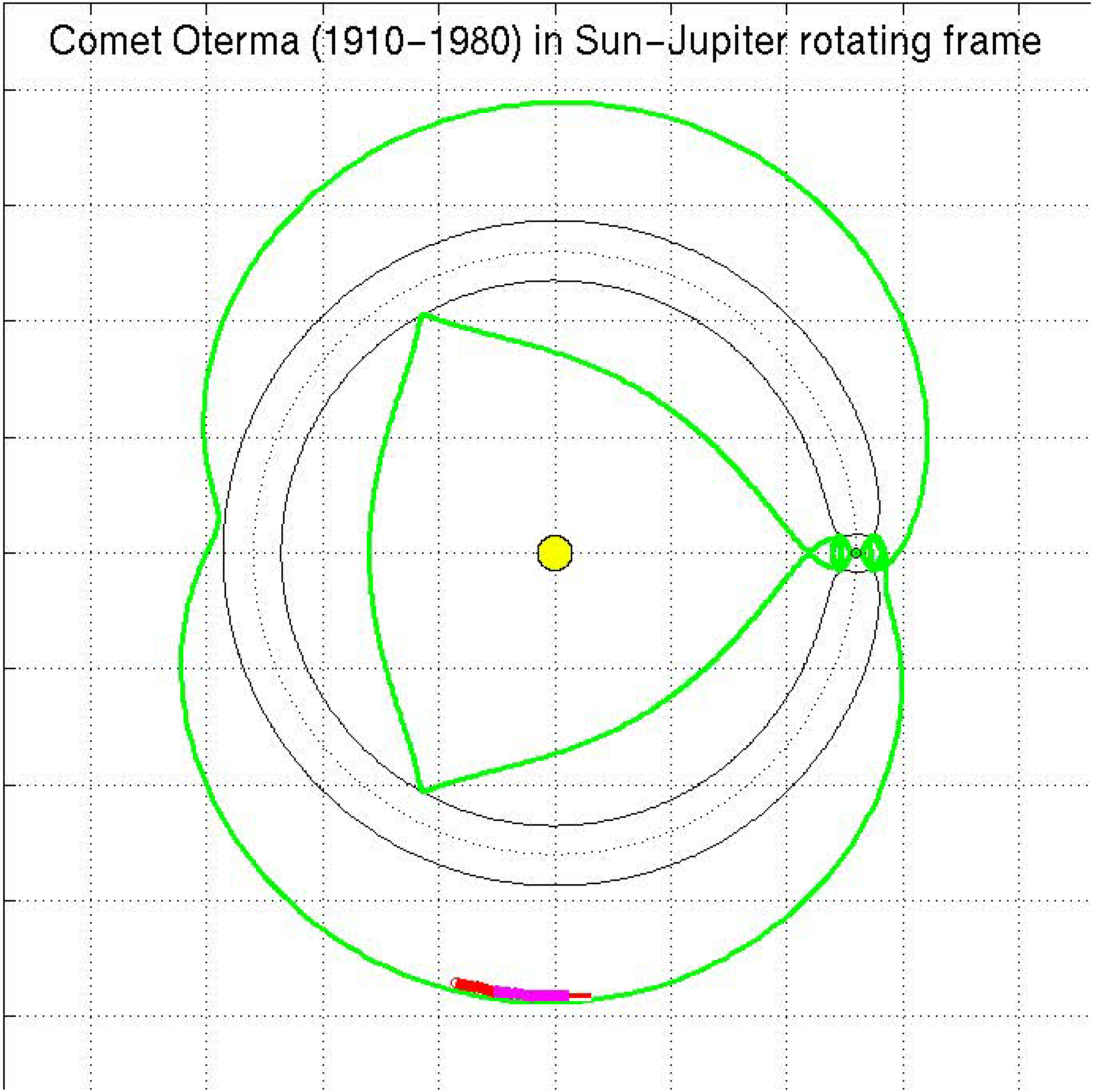
Comet Oterma Under Jupiter IPS Control



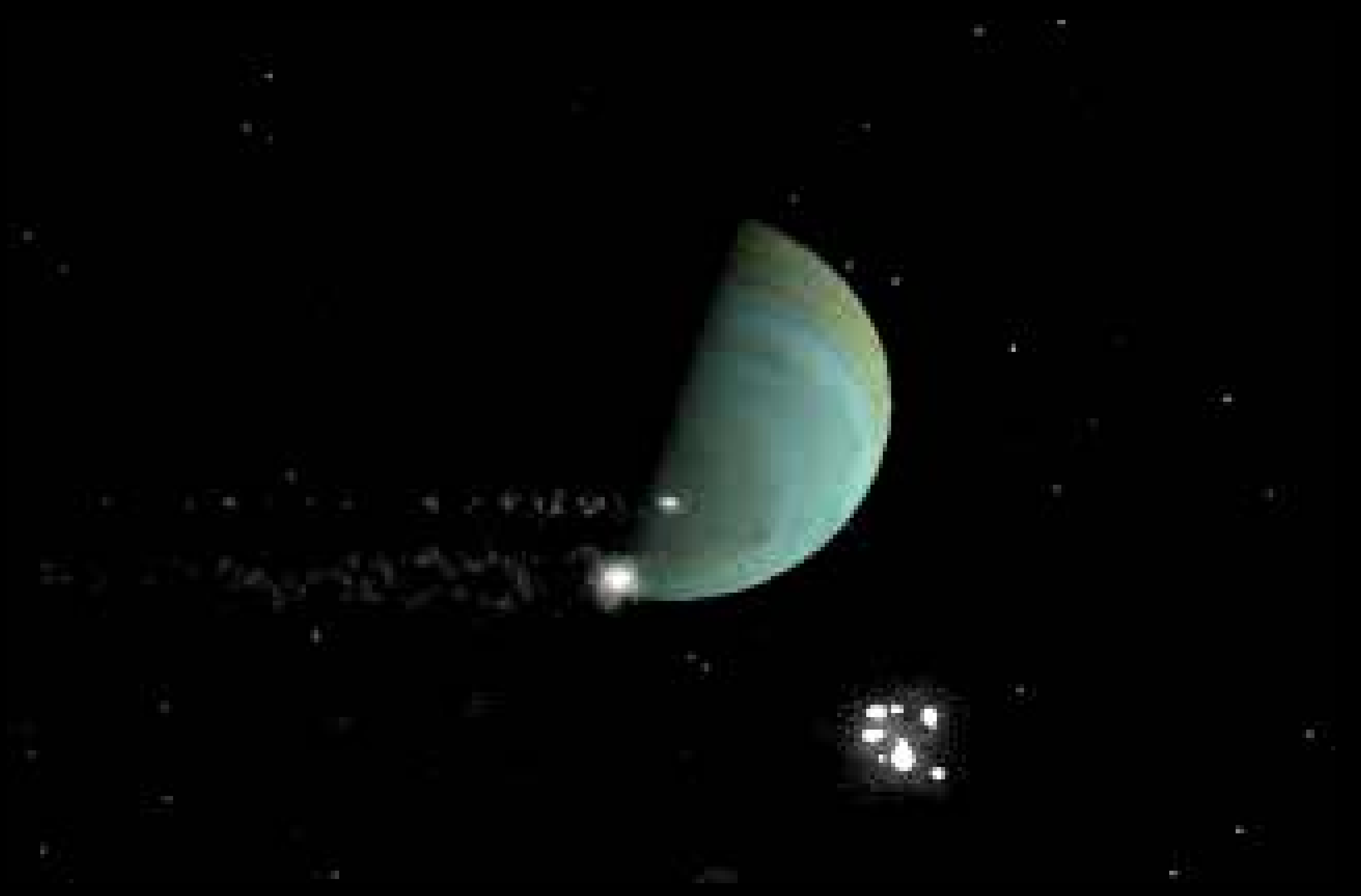
- **Inertial Frame Is Unrevealing**
- **Rotating Frame Shows Pattern**
  - **Oterma follows a homoclinic-heteroclinic chain**
  - **Chaotic orbit**

Comet Oterma (1910–1980) in Sun–centered inertial frame




Comet Oterma (1910–1980) in Sun–Jupiter rotating frame

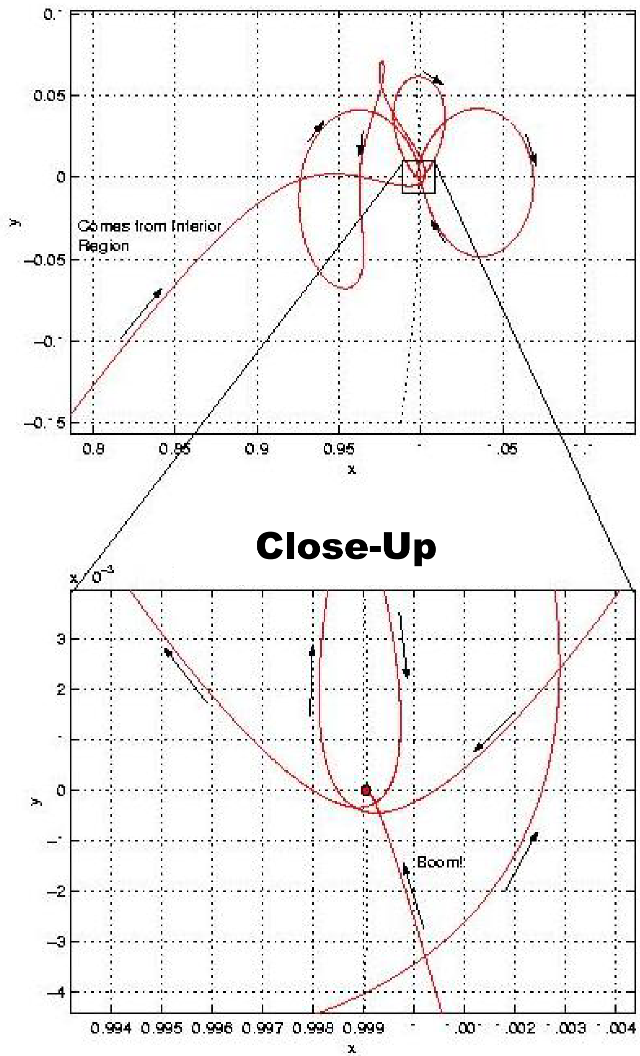
Shoemaker-Levy 9 Collision



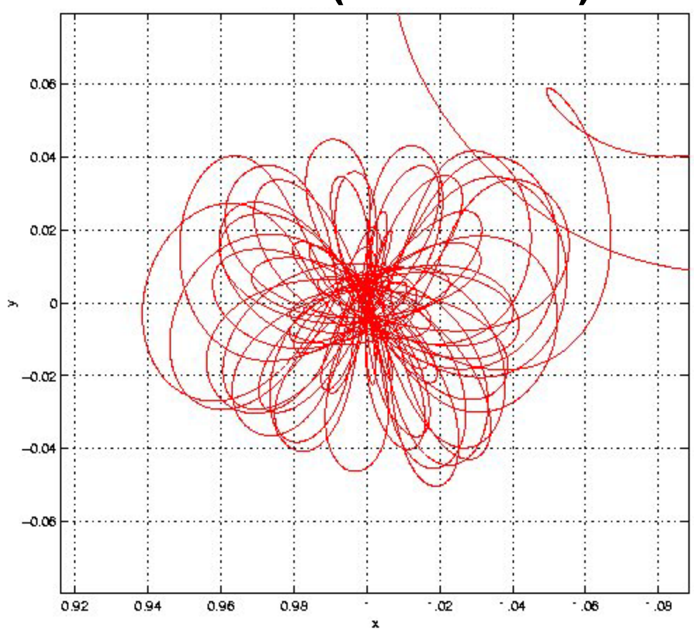
Simulation of *SL9* Collision

- ***Tubes intersect planets***
  - **Compare *SL9* orbit (below) to computed orbit of similar energy (right)**

***SL9*–like orbit (ref: Thrasher)**



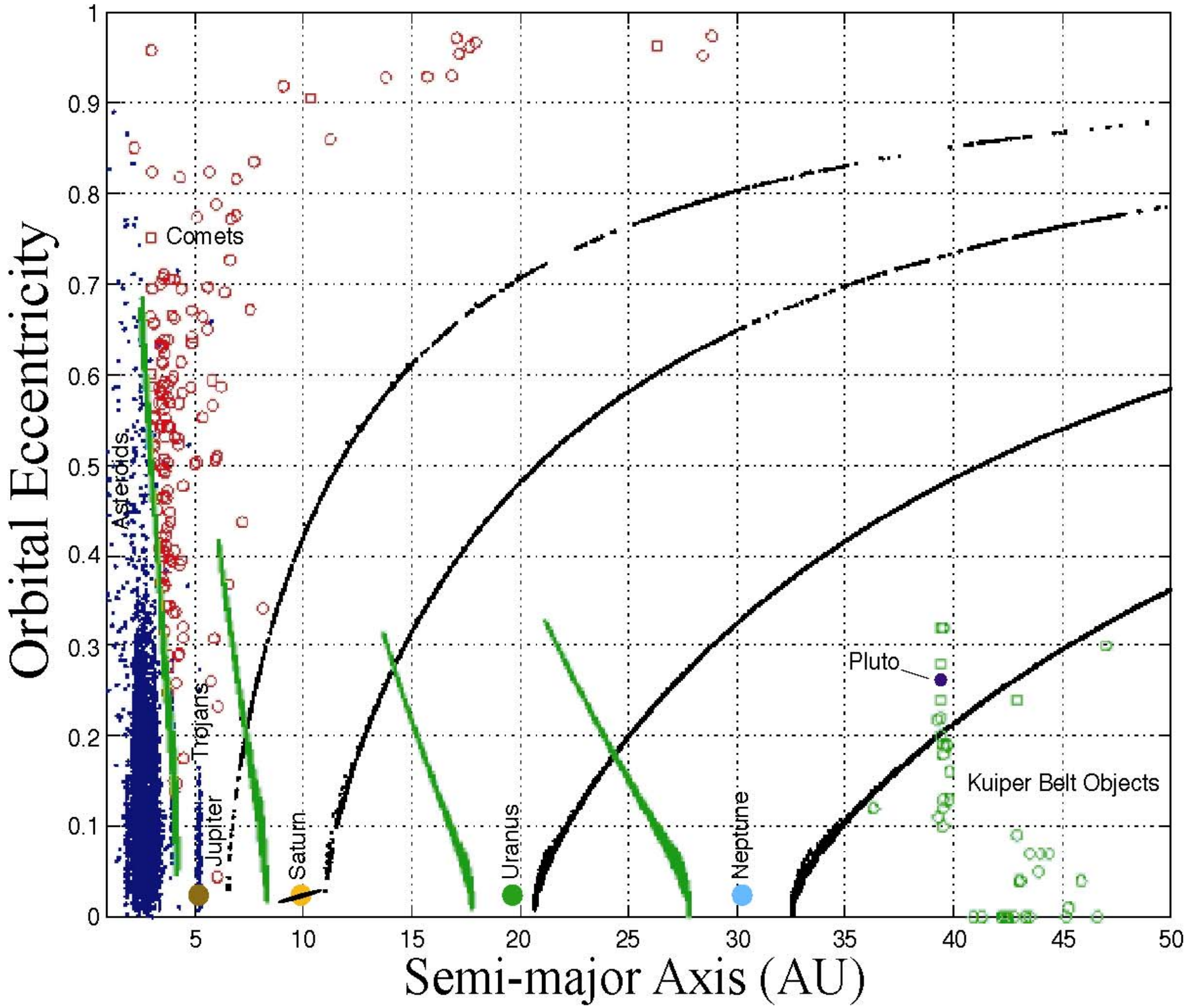
***SL9* orbit (ref: Chodas)**



Lunar L_1 Gateway

IPS & Transport in the Solar System

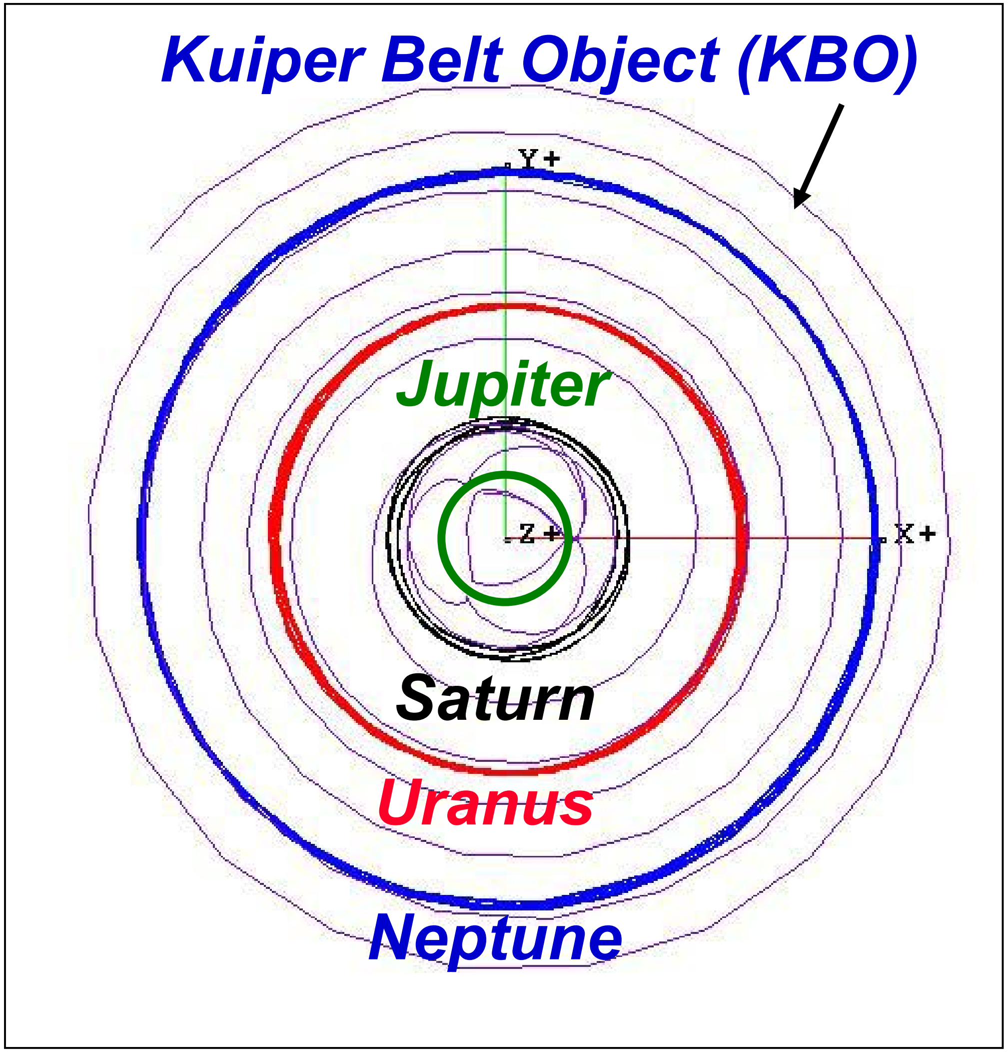
Poincare Section of the InterPlanetary Superhighway (IPS)



Legend

- L_1 IPS Orbits
- L_2 IPS Orbits
- Comets
- Asteroids
- Kuiper Belt Objects

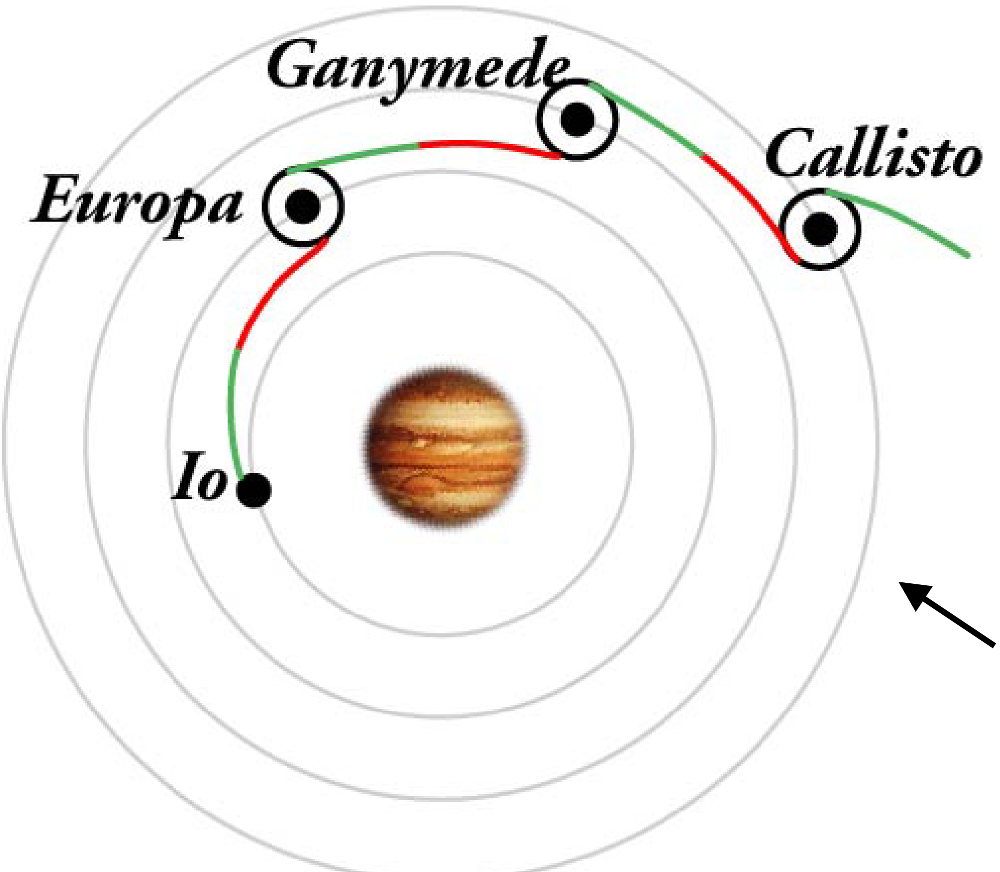
Fast Transport from Kuiper to Asteroid Belt



Kuiper to Asteroid Belt (ref: Lo, Thomas, Turpin)

- **Only 250 years**
- **Origin of Jupiter Comets**
- **Replenish Asteroid Belt**
- **Escape from Solar System**
- **Suggests New Low Thrust Algorithm?**

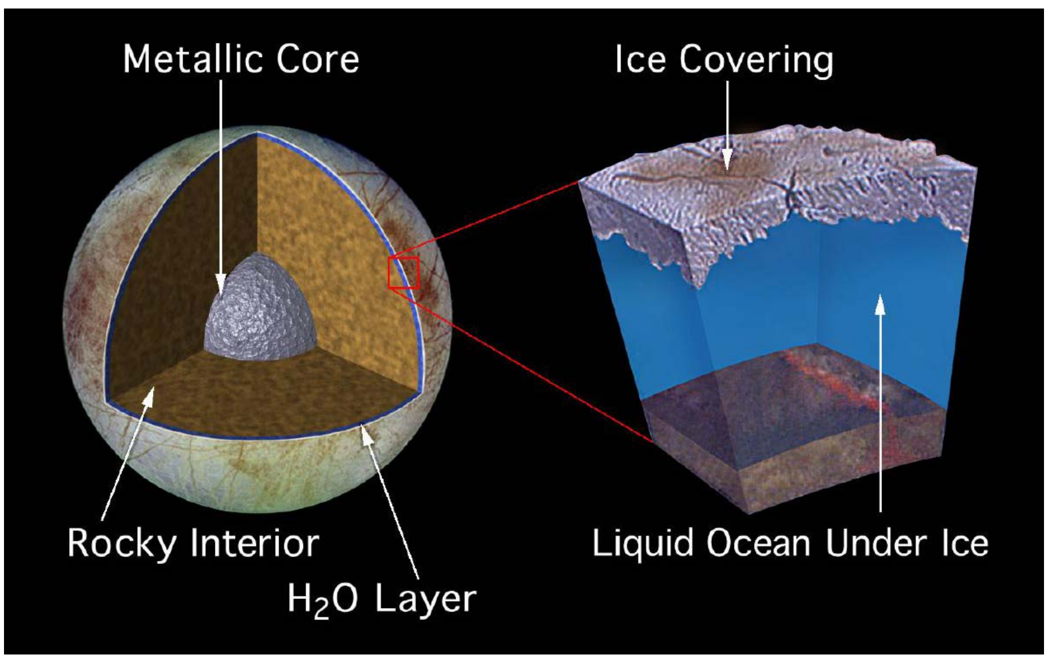
Petit Grand Tour of Jovian Moons

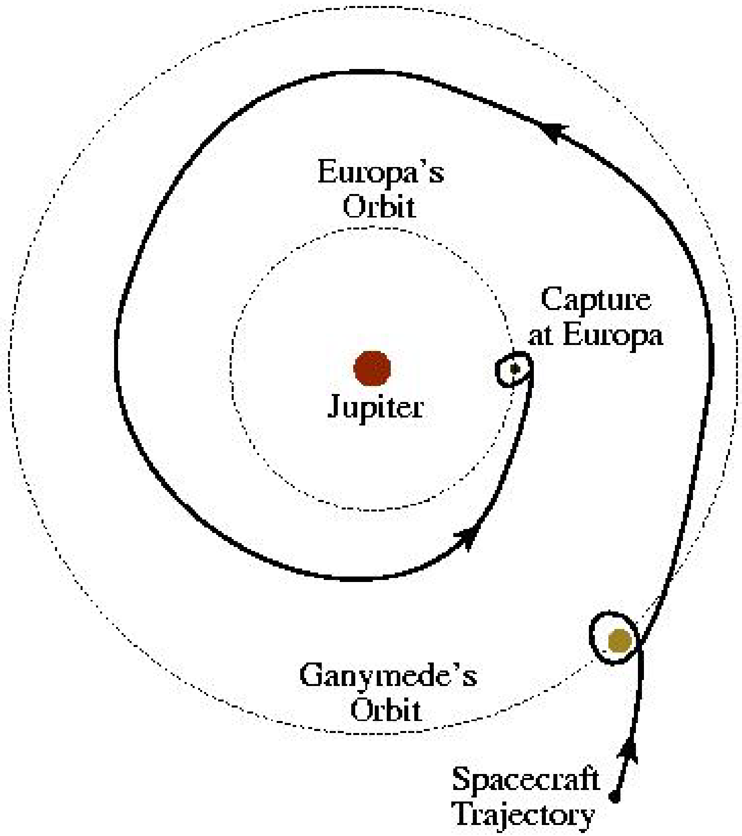


- Similar path can be constructed for a new mission concept: ***the Petit Grand Tour***
- Serial low energy captures, transfers between moons
- Near circular transfer orbits avoid Jupiter radiation
- ***Available at all outer planets***

Jovian Superhighways and Europa Missions

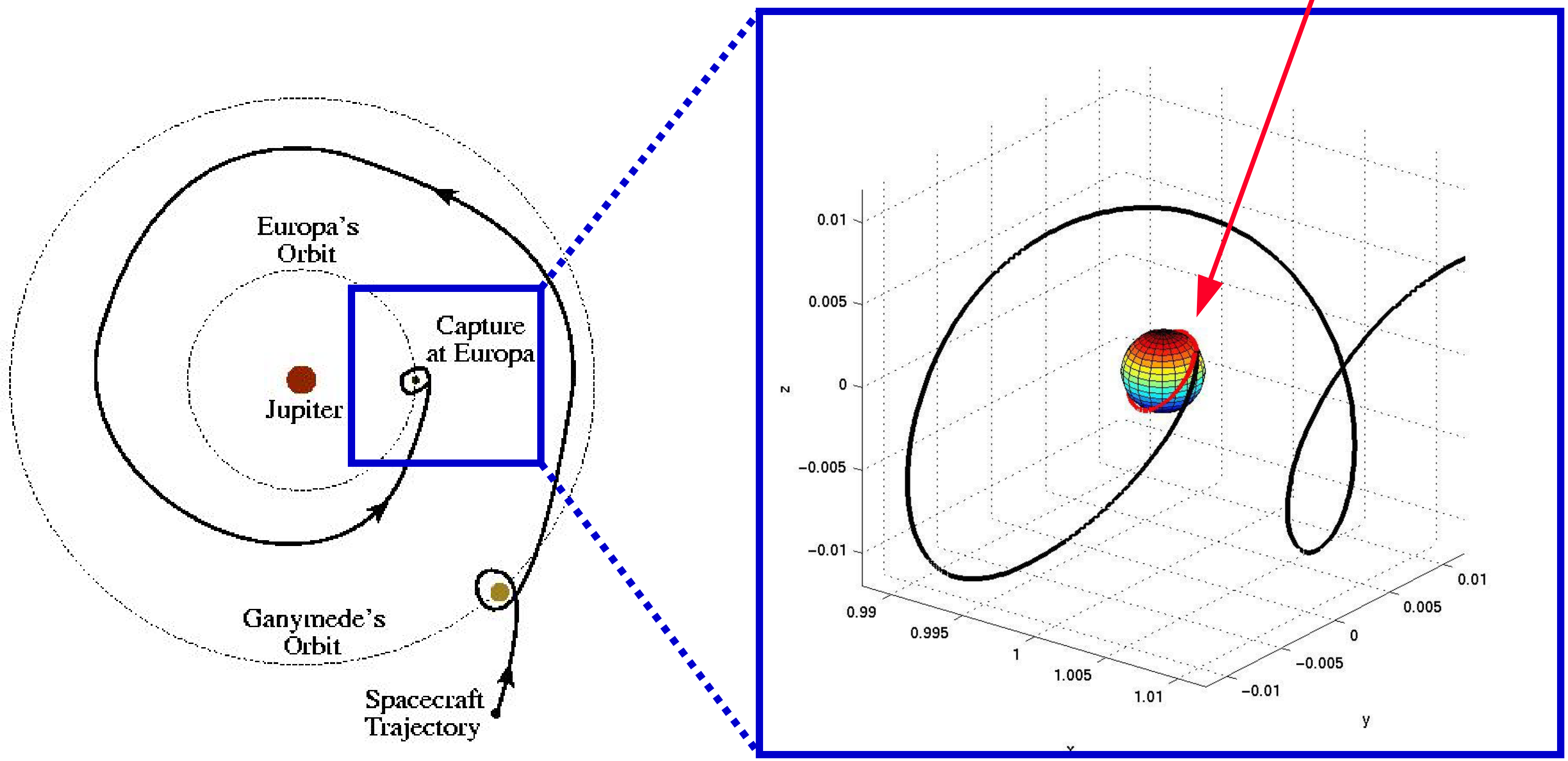
- ***Petit Grand Tour***
  - **May Be Useful to Europa Missions**
    - **Possible oceans, life?**
  - **Propellant Savings**
    - **Transfer ΔV ~ 0.5 Hohmann**
    - **Ref: Koon, Lo, Marsden, Ross [2002]**
  - **Faster Trajectory Design**



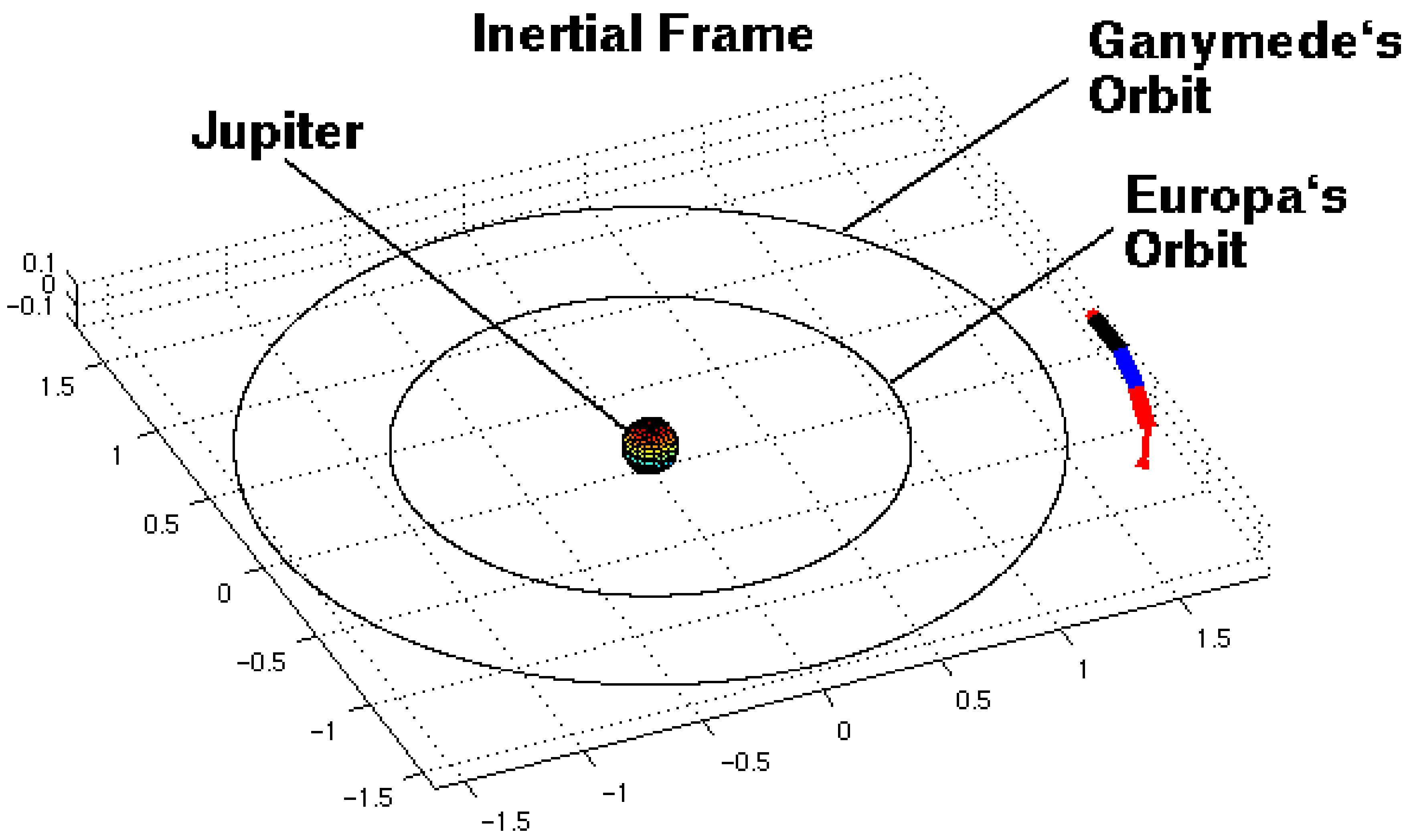


Jovian Superhighways and Europa Missions

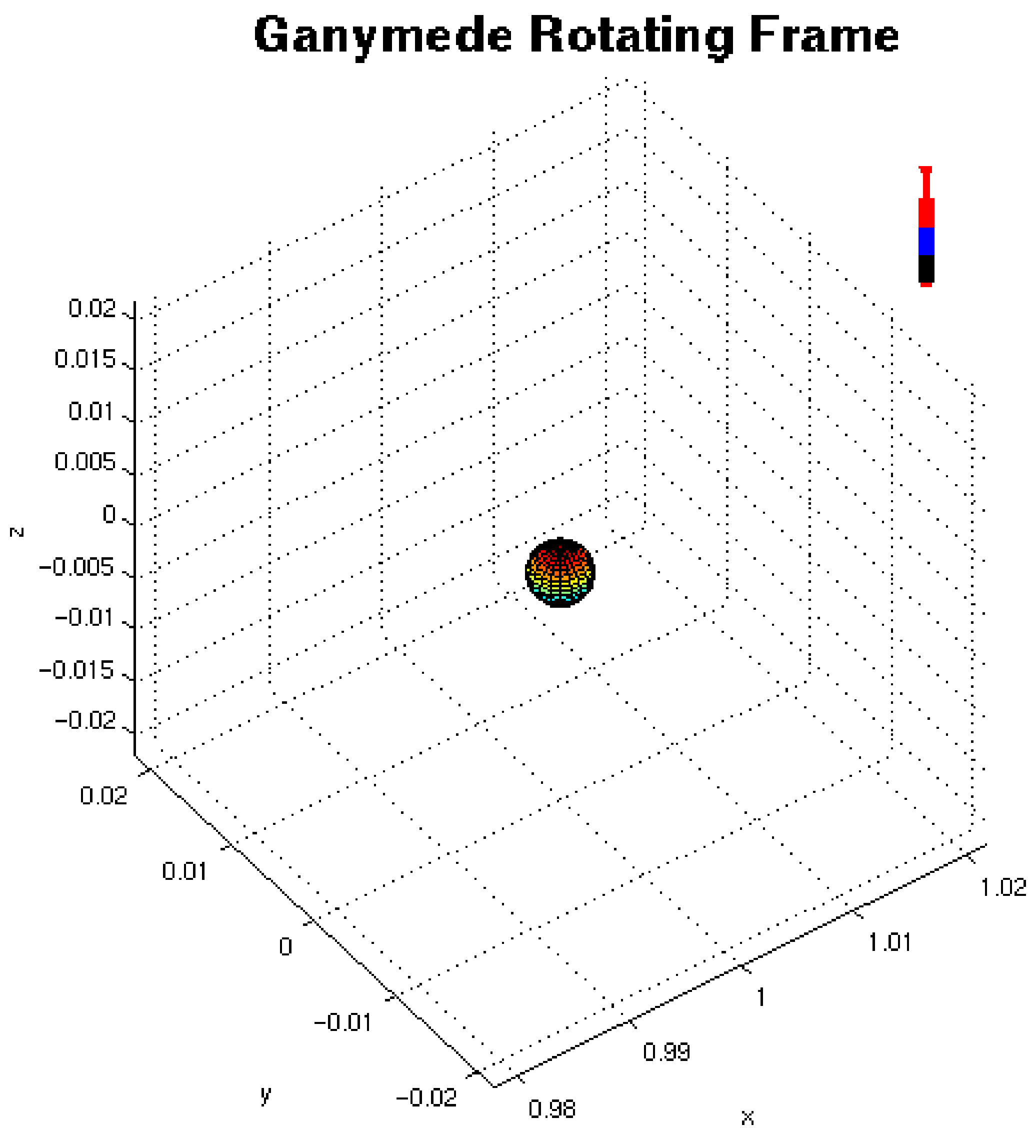
- **New Understanding of 3D Transport Provides Systematic Design of High Inclination Low Energy Capture into Europa Orbit**
- **Gomez, Koon, Lo, Marsden, Masdemont, Ross [2001]**



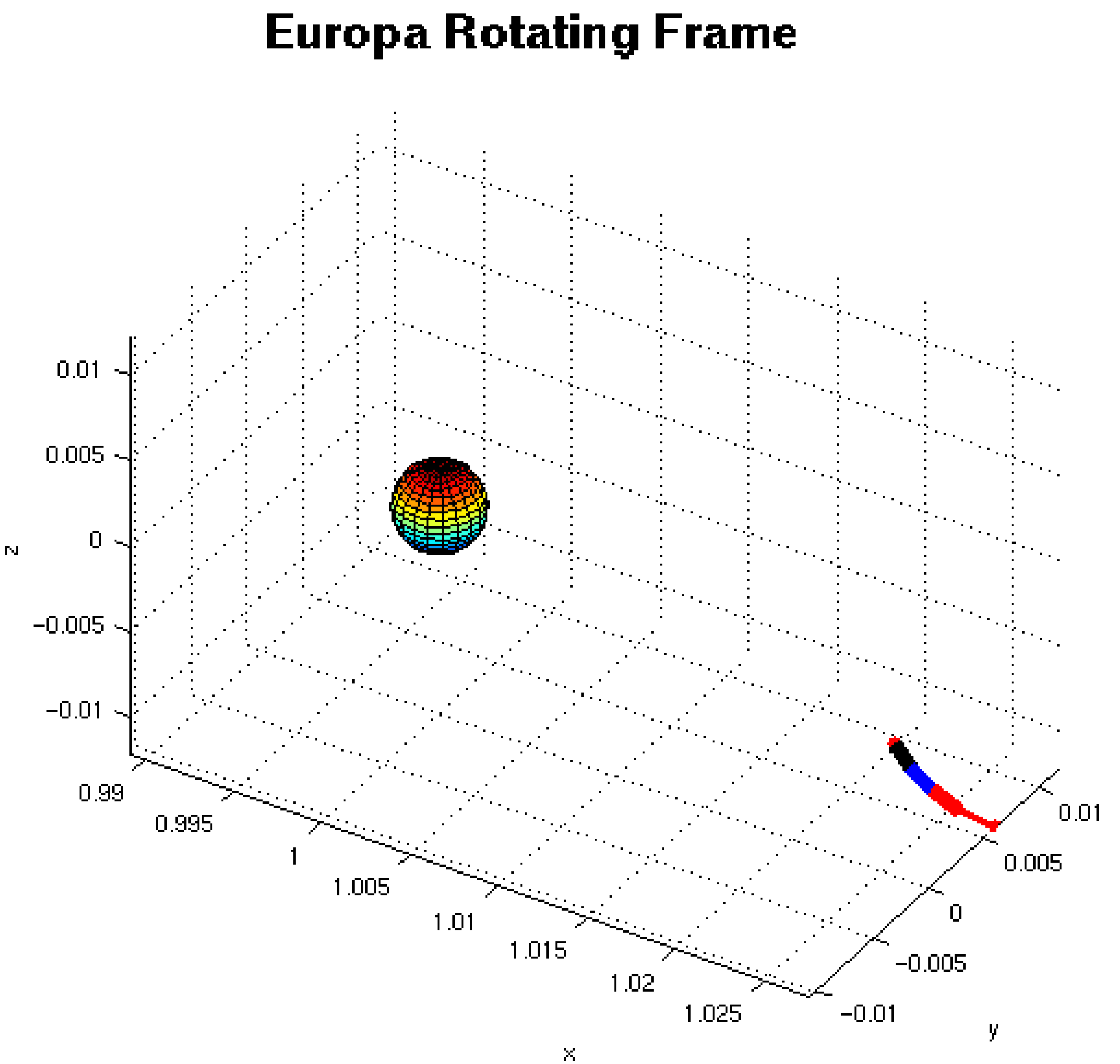
Jovian Superhighways and Europa Missions



Jovian Superhighways and Europa Missions

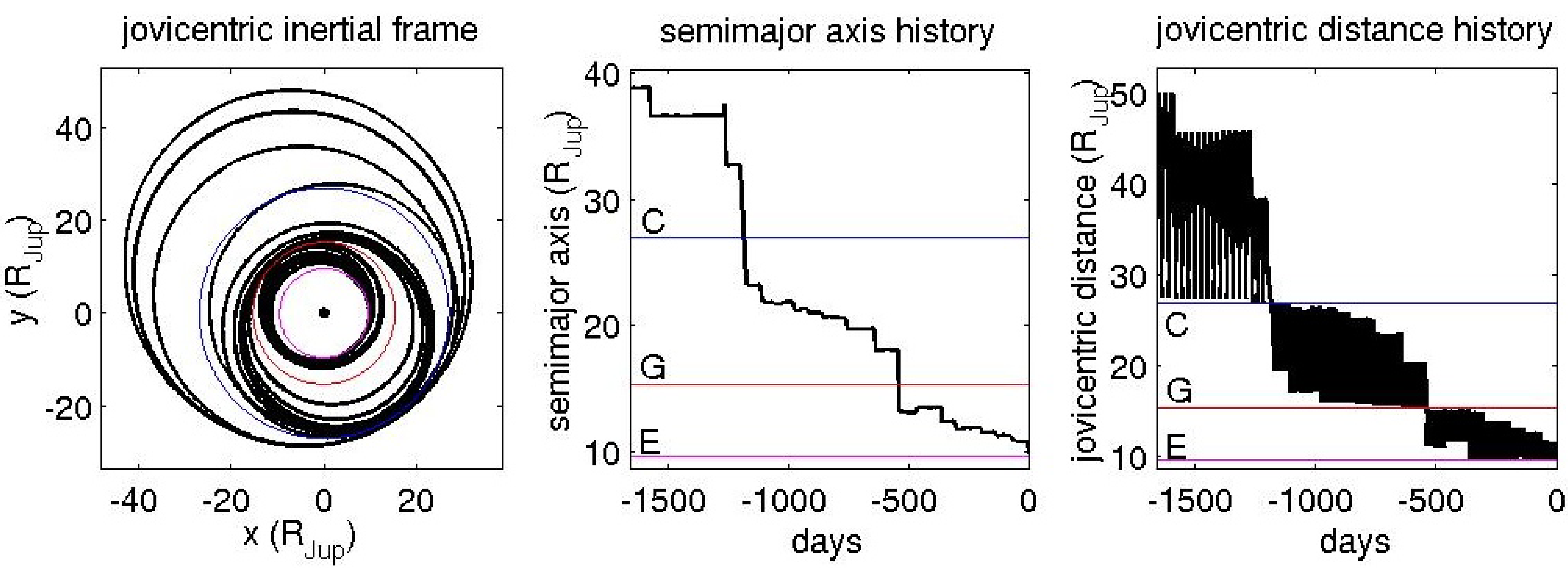


Jovian Superhighways and Europa Missions



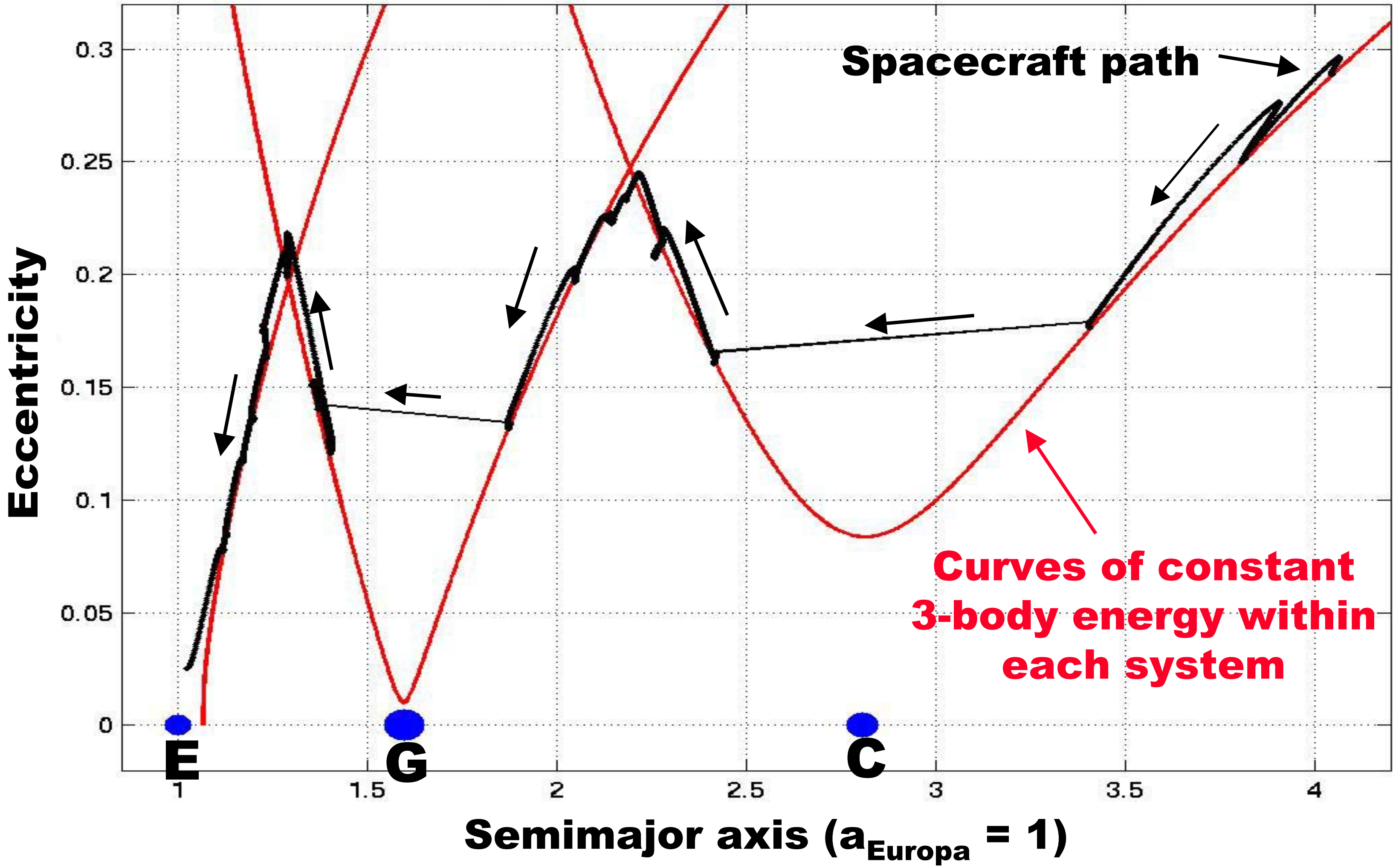
Fuel Usage Drastically Reduced

- **New computation (Ross, 2002)**
- **Serial visits to Galilean moons, final Europa capture**
  - **Total Delta-V ~ 20 m/s!**
  - **1500 days transfer time (can be greatly reduced)**



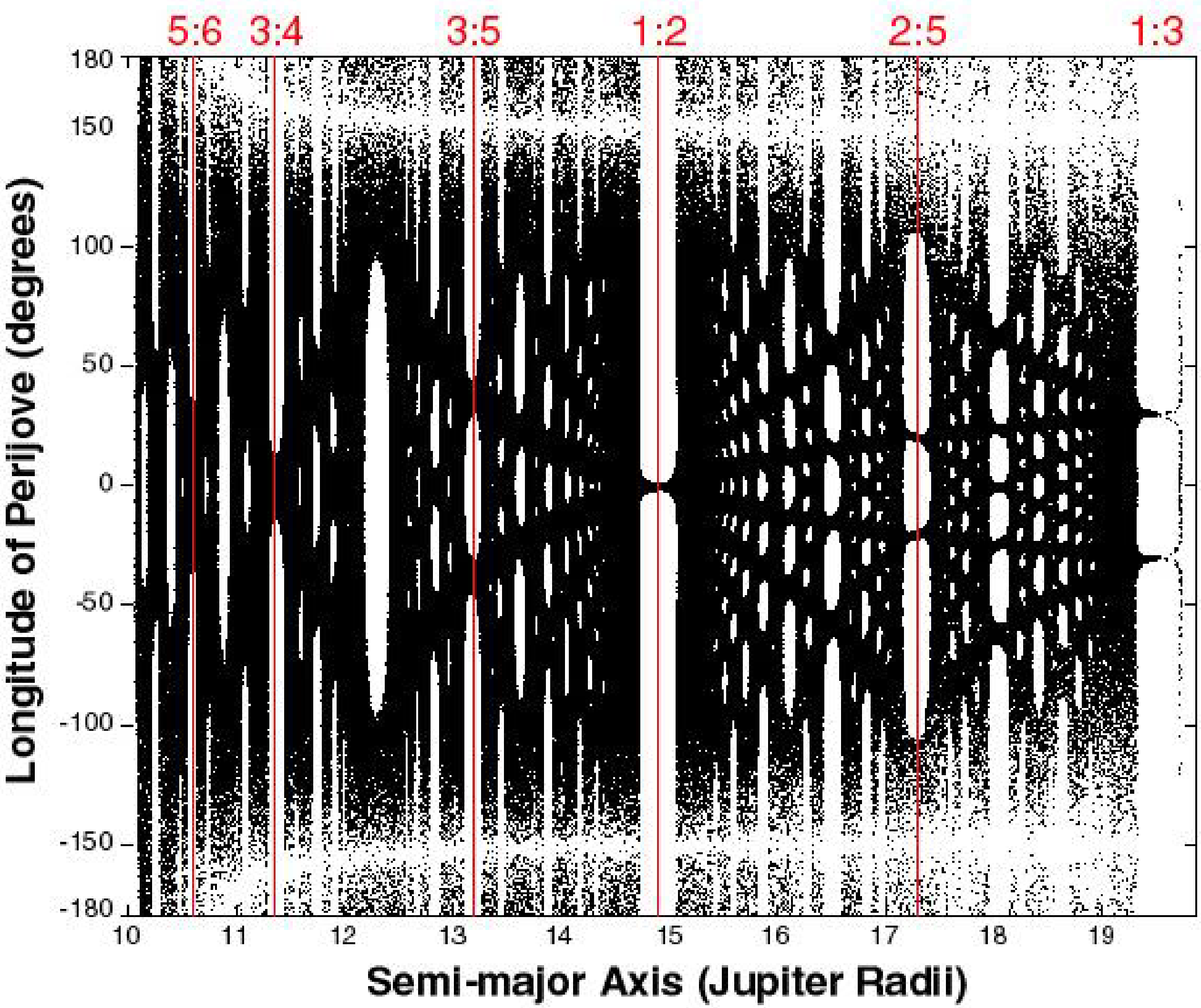
Transport Along Energy Surface

Spacecraft jumping between *resonances* on the way to Europa



Jumping Between Resonances on an Energy Surface

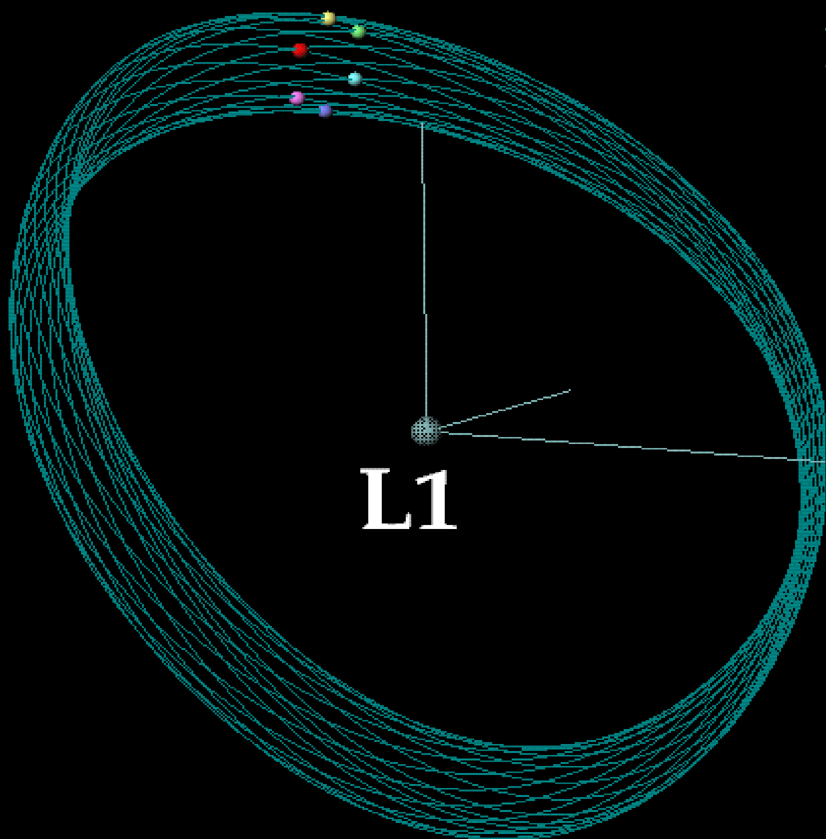
Poincare section revealing *resonances* on the way to Europa



Lunar L_1 Gateway Station

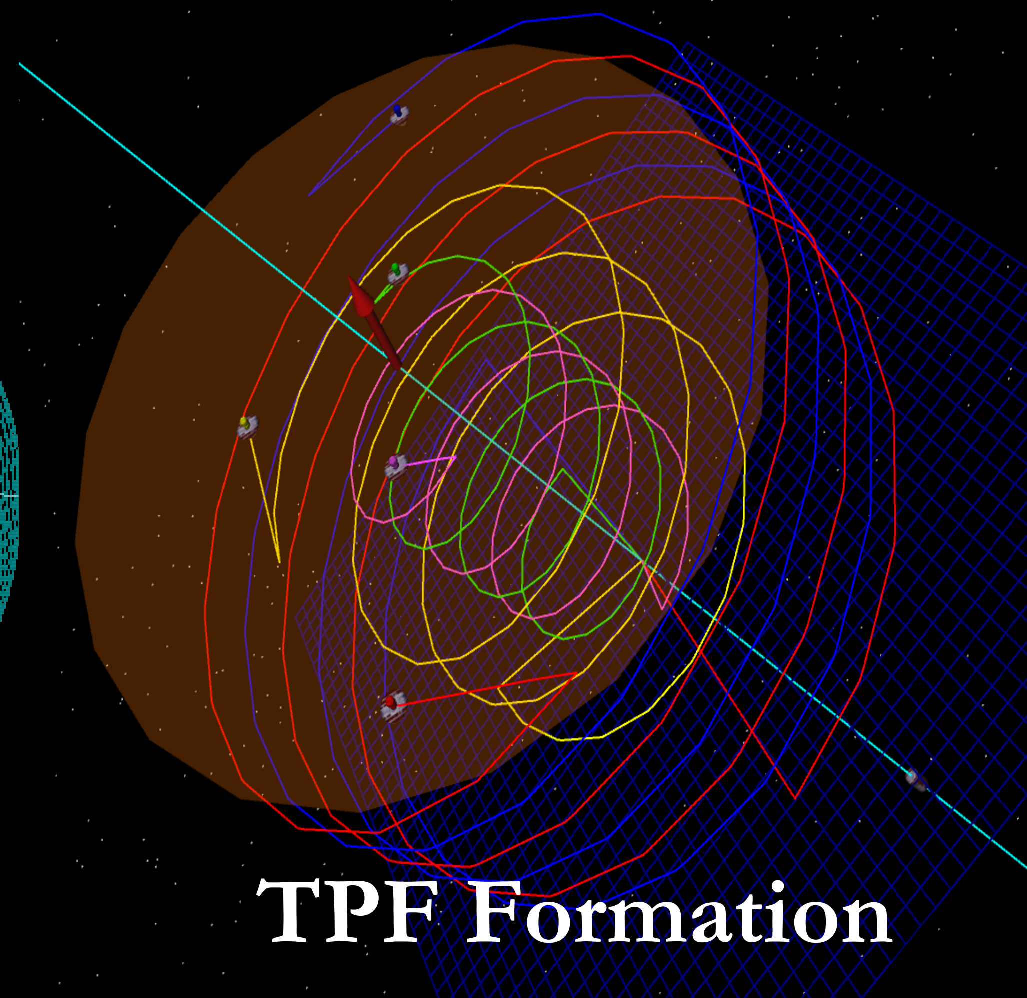
The closest rest stop on the
InterPlanetary Superhighway

Future Constellations & Formation Flight Near Sun-Earth L_2



Quasihalo Orbits

Ref: Howell, Barden, et al. [2001]

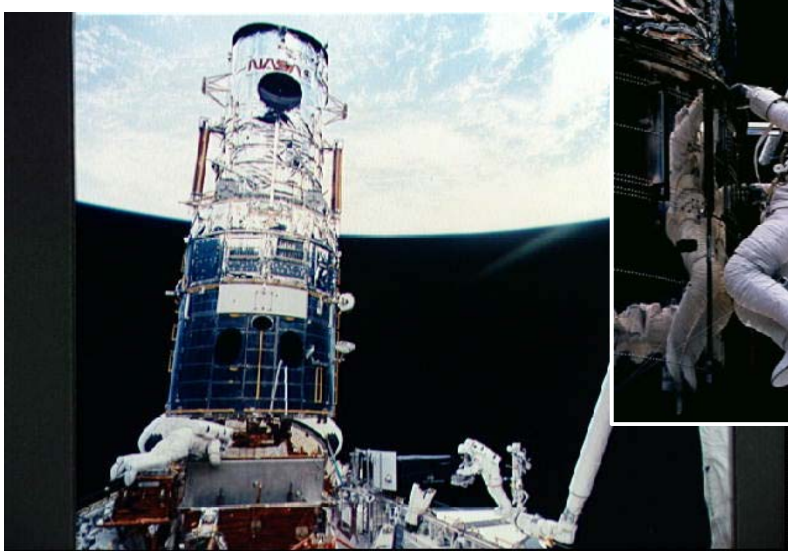


TPF Formation

Ref: Lo, Masdemont, et al. [2001]

Problem:
Human Service to Libration Point Missions

- 3 Month Transfers to Earth L_2 Too Long for Humans
- Short Transfers Too Costly, Difficult
- Infrastructure Too Expensive
- Take Smaller Step from LEO



STA-103 astronauts repairing the Hubble Space Telescope

Solution:
Human Service from Lunar L_1 Gateway

- **Send S/C Between Lunar L_1 Gateway Hub and Earth L_2 via the Interplanetary Superhighway**
  - **50 m/s energy difference btwn LL_1 (Lunar) and EL_2 (Earth)**
- **Lunar L_1 Orbits Accessible from Earth, LEO, Moon**
  - **Short Transfers: Hours to 7 Days**

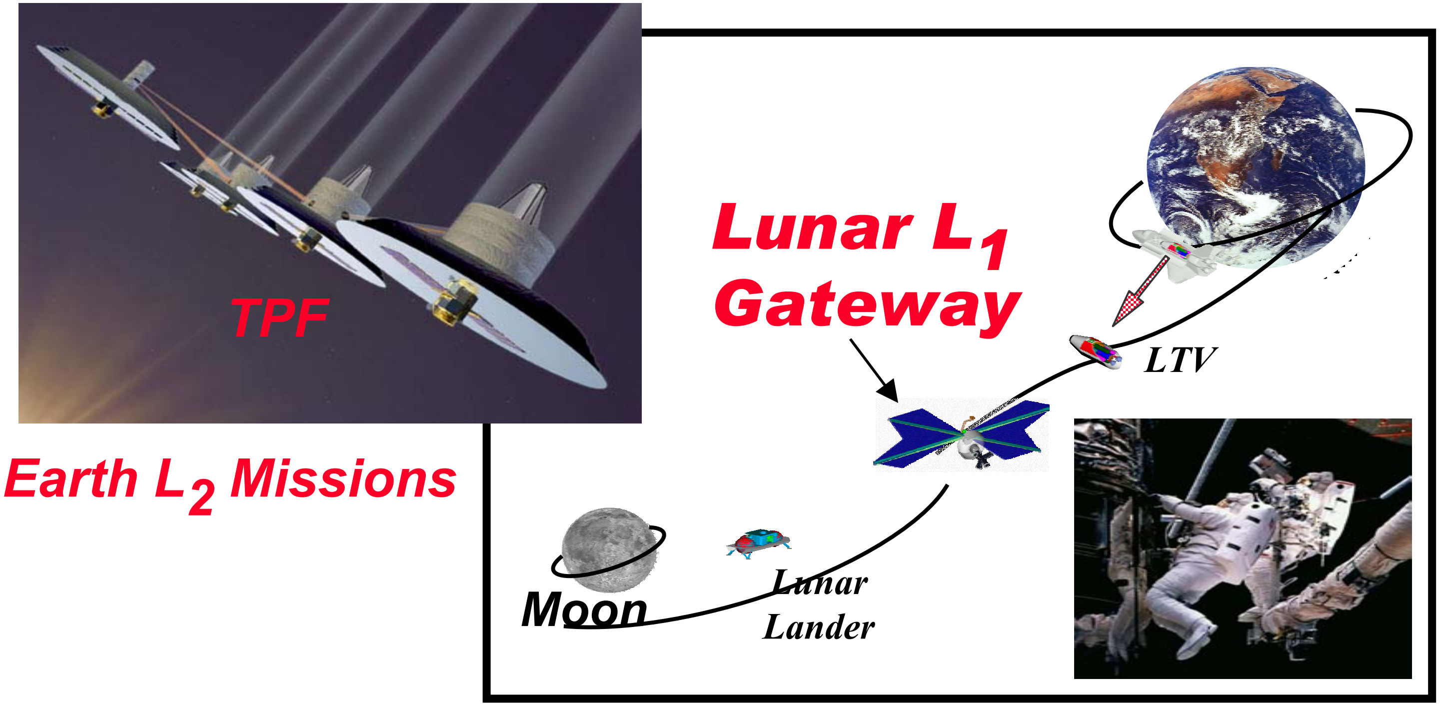
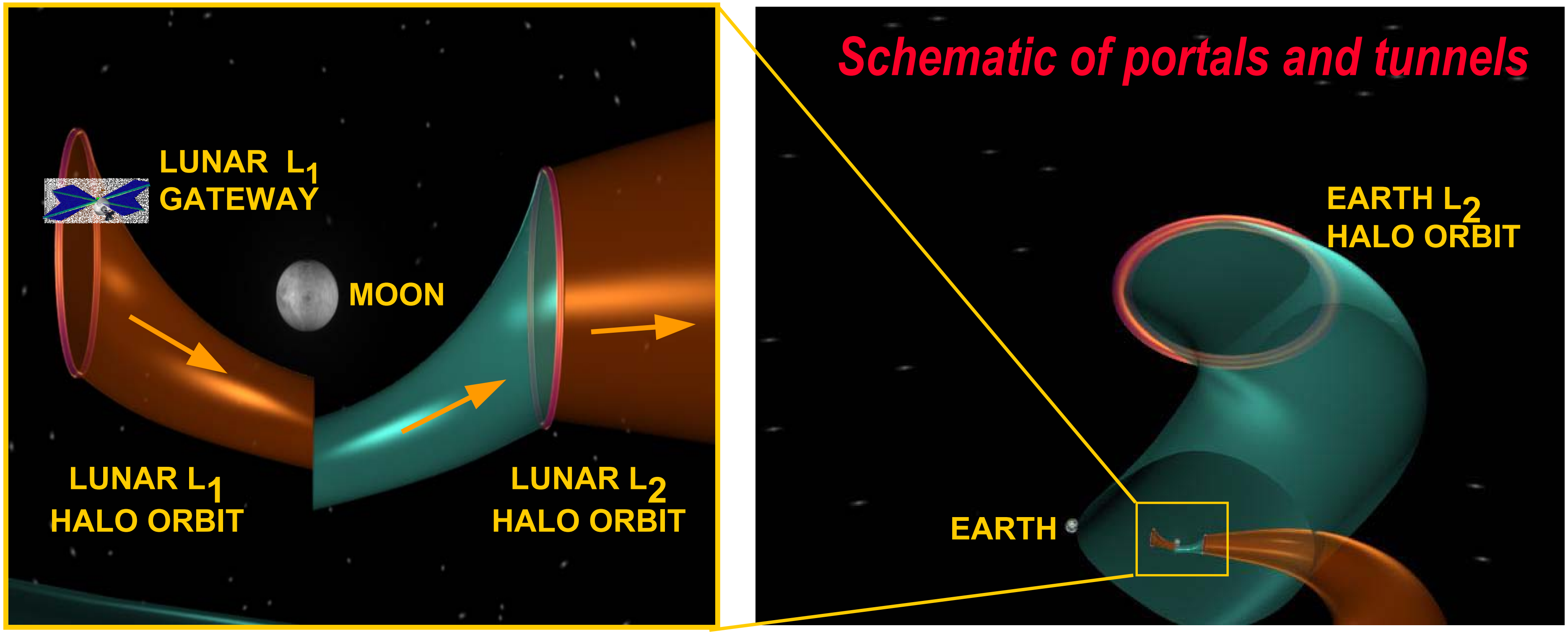


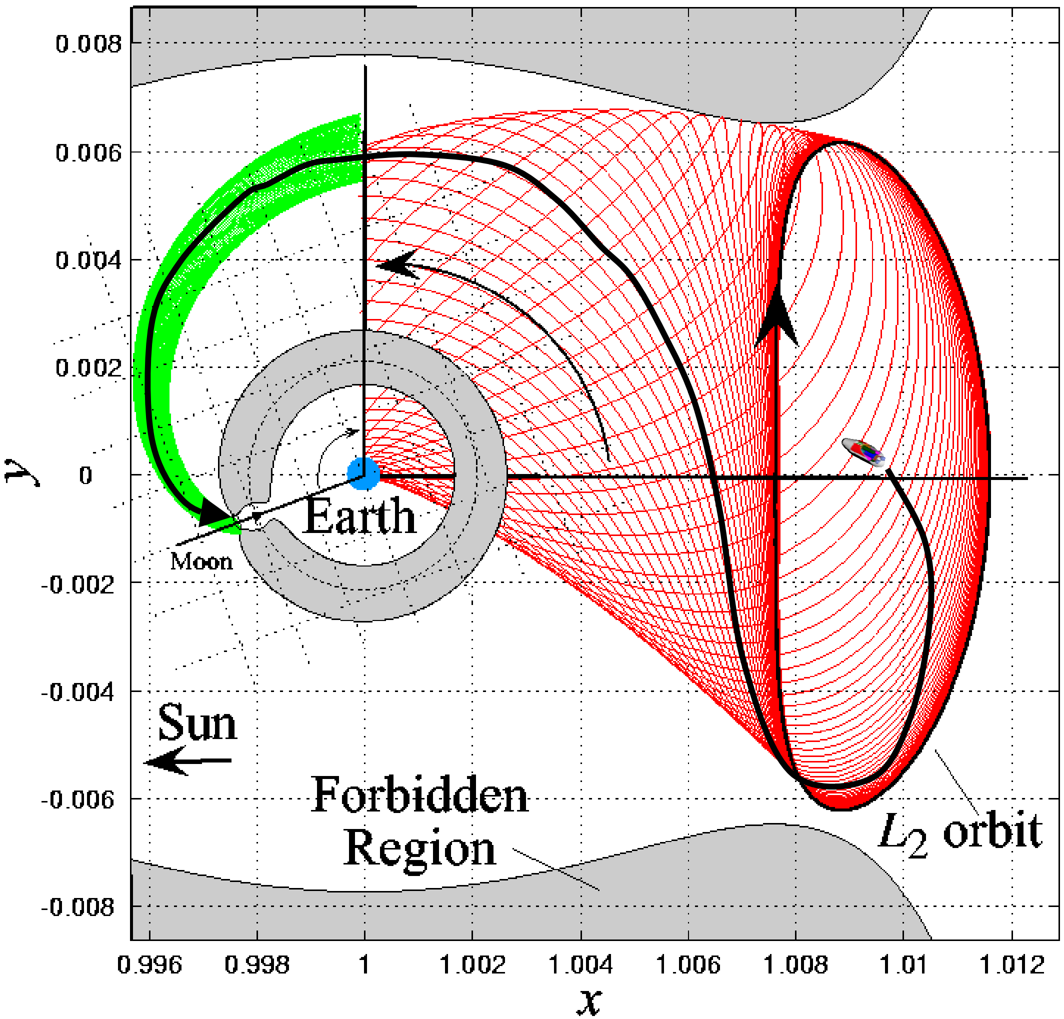
Figure based on Condon and Pearson [2001]

Use InterPlanetary Superhighway

- ***Interplanetary Superhighway: Low Energy Portals & Tunnels Generated by Lagrange Points***
- ***Portals = Halo Orbits! Tunnels = Invariant Manifolds***



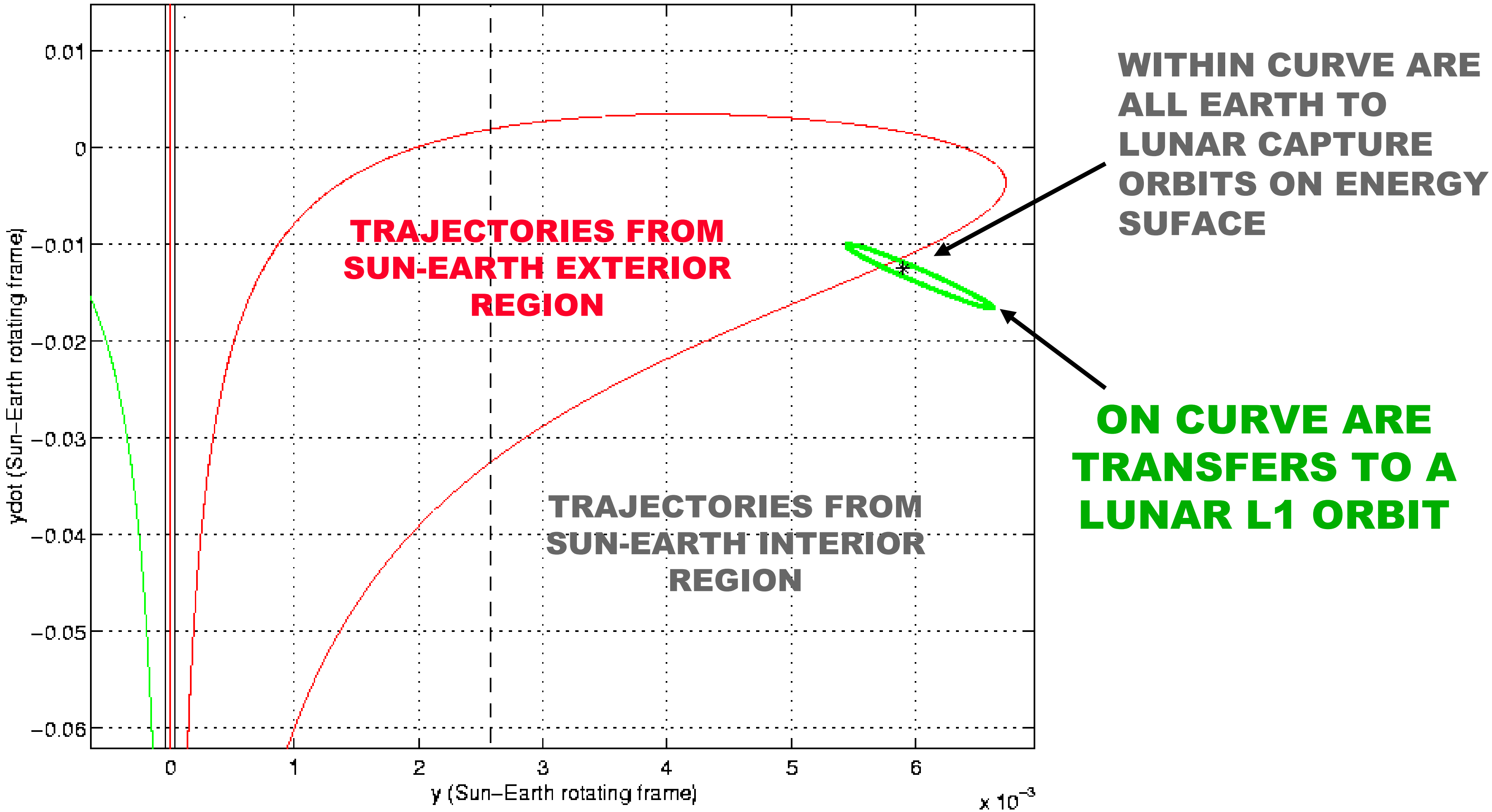
Earth-Moon IPS Interchange



- ***Easy Return of S/C from L2 to***
  - **Lunar L1/L2 Orbit**
  - **Lunar Capture Orbit**
  - **Earth Return Orbit**
- ***Potential for Human Servicing & Replacements***
- ***Staging for Interplanetary Launch***

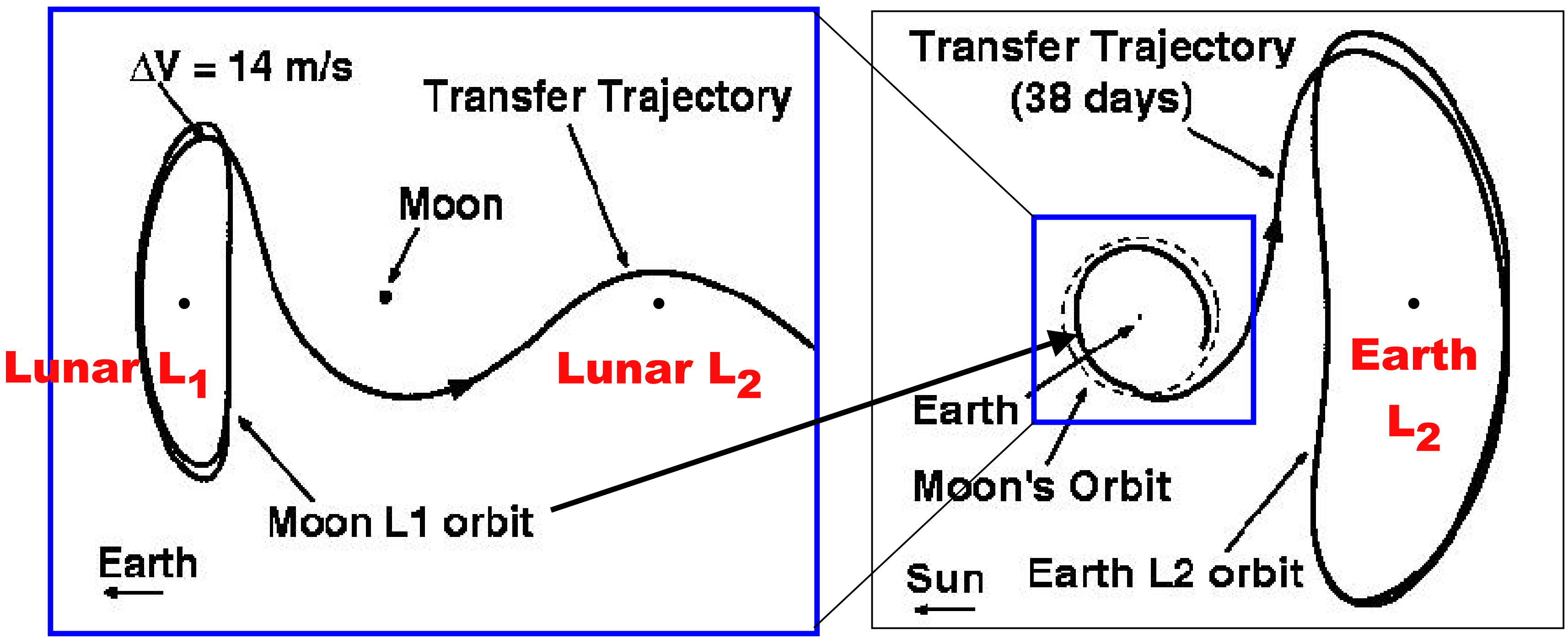
Construction of Lunar L1 Transfer Orbit

A CROSS SECTION OF THE SUN-EARTH AND EARTH-MOON IPS PARTITIONS THE ORBITAL DESIGN SPACE INTO CLASSES



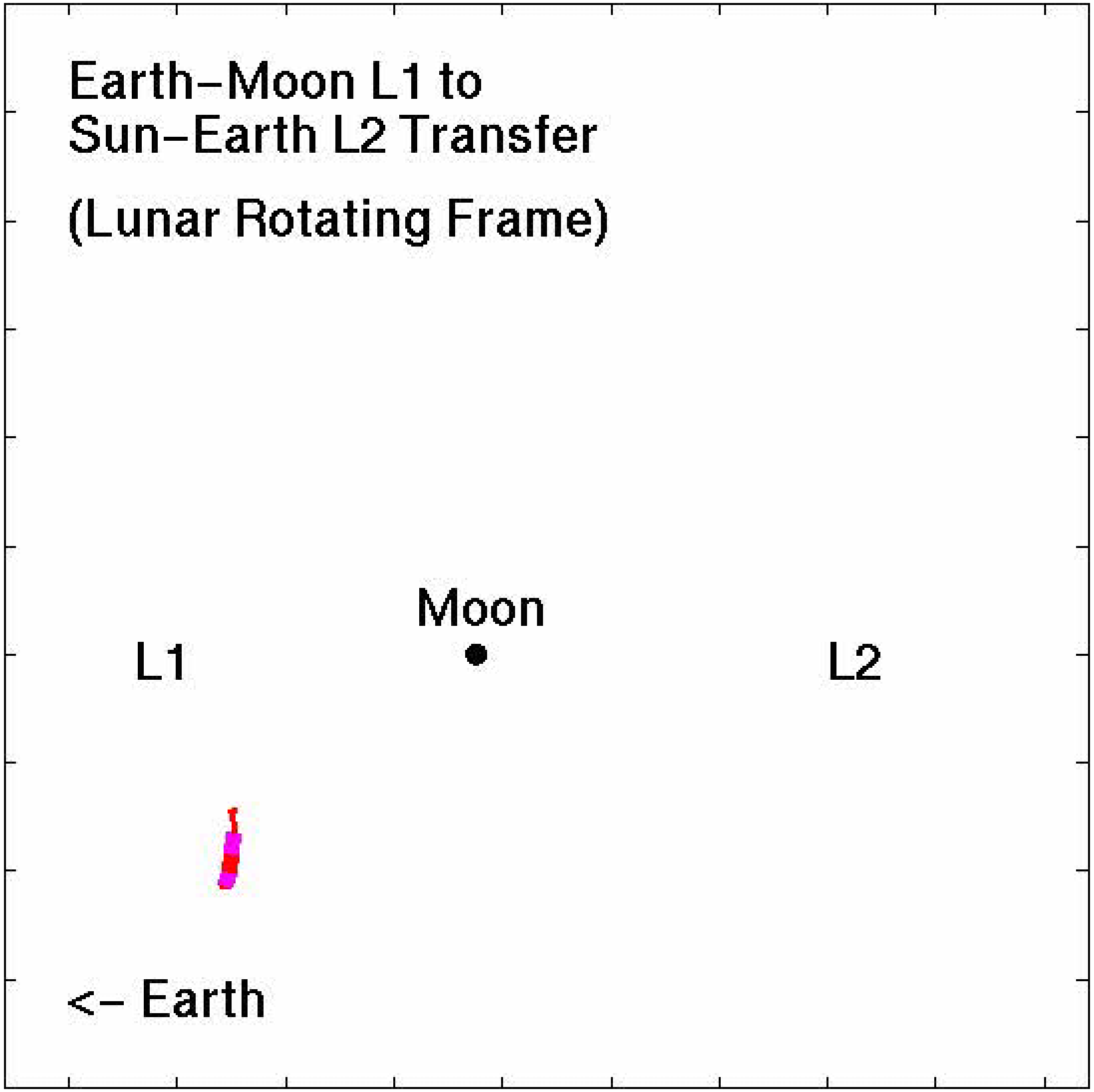
Lunar L_1 to Earth L_2 Orbit Transfer

- **Build Instruments & S/C at Lunar L_1 Station**
- **Transfer S/C from LL_1 Station to Earth-L_2 LIO**
  - **LIO = Libration Orbit**
- **Service S/C at Earth L_2 LIO from LL_1 Gateway Hub**

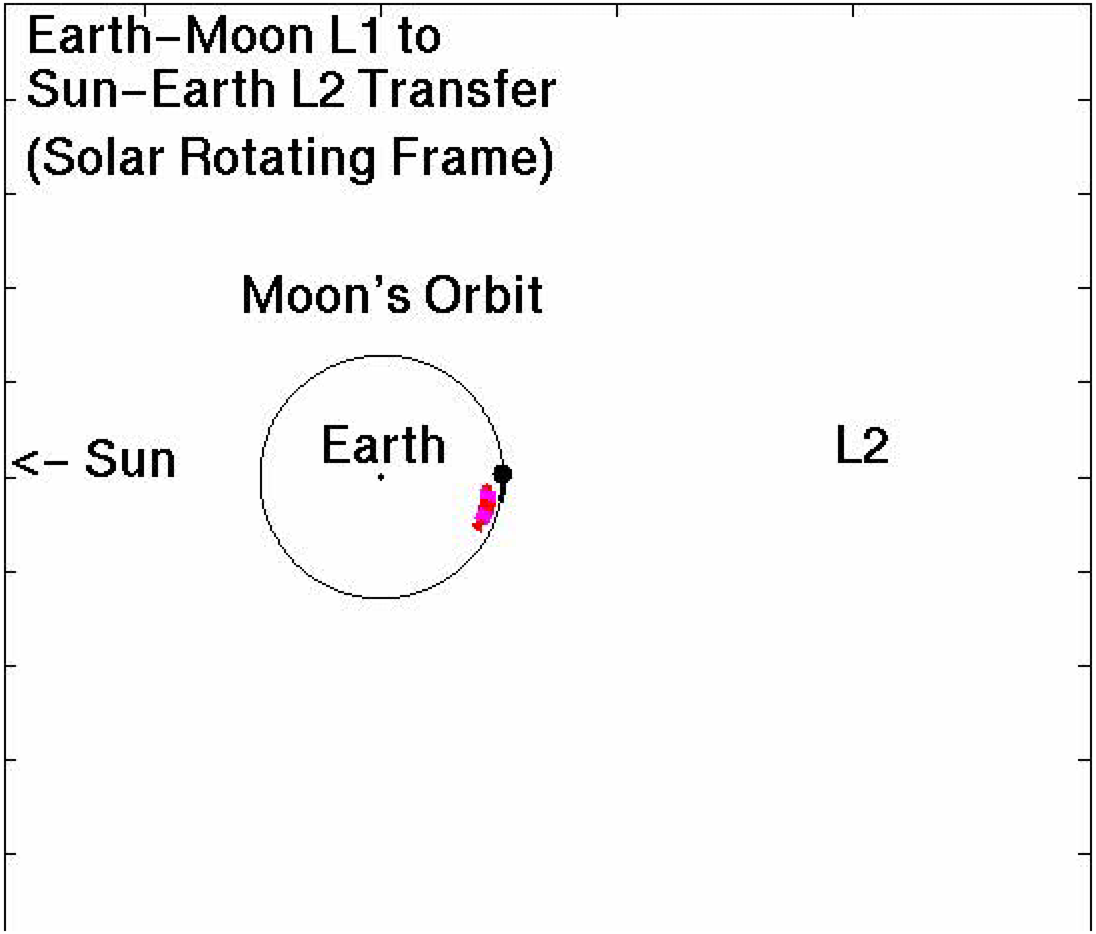


Lunar Rotating Frame **Earth Rotating Frame**

Lunar L_1 to Earth L_2 Orbit Transfer



Lunar L_1 to Earth L_2 Orbit Transfer

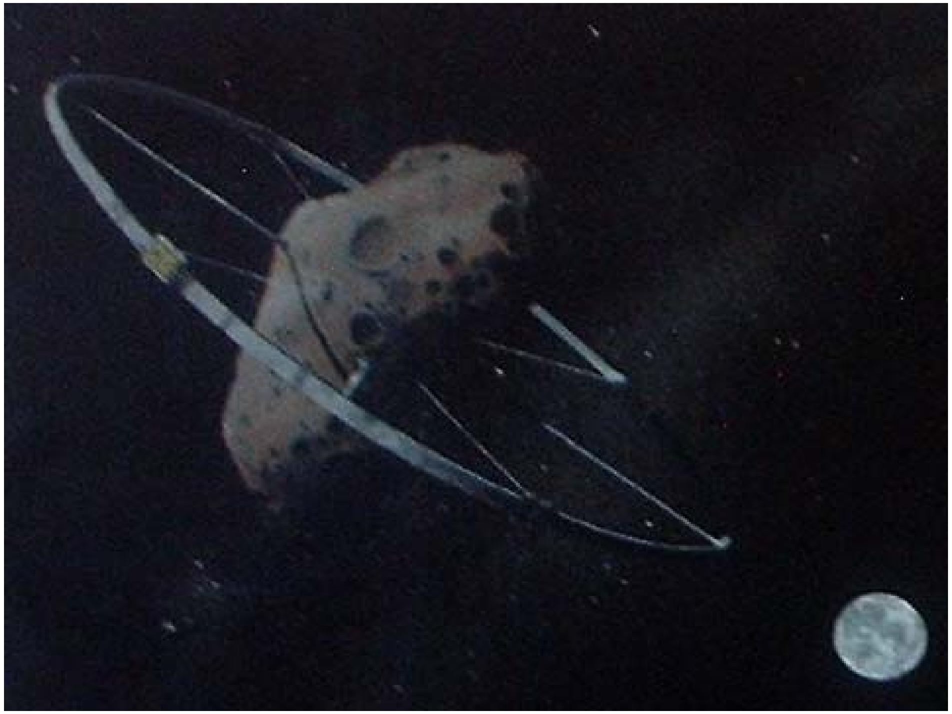


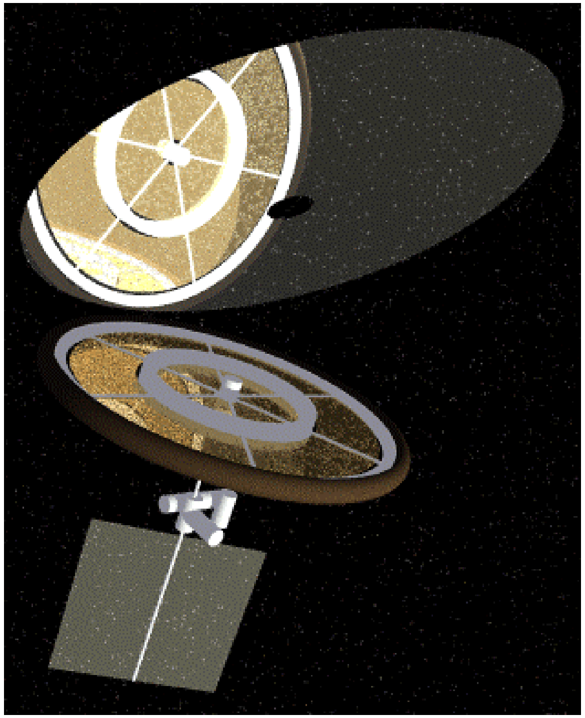
Servicing Earth L2 Missions at Lunar L1 Gateway Station

Near Earth Asteroids: Armageddon Or Opportunity?

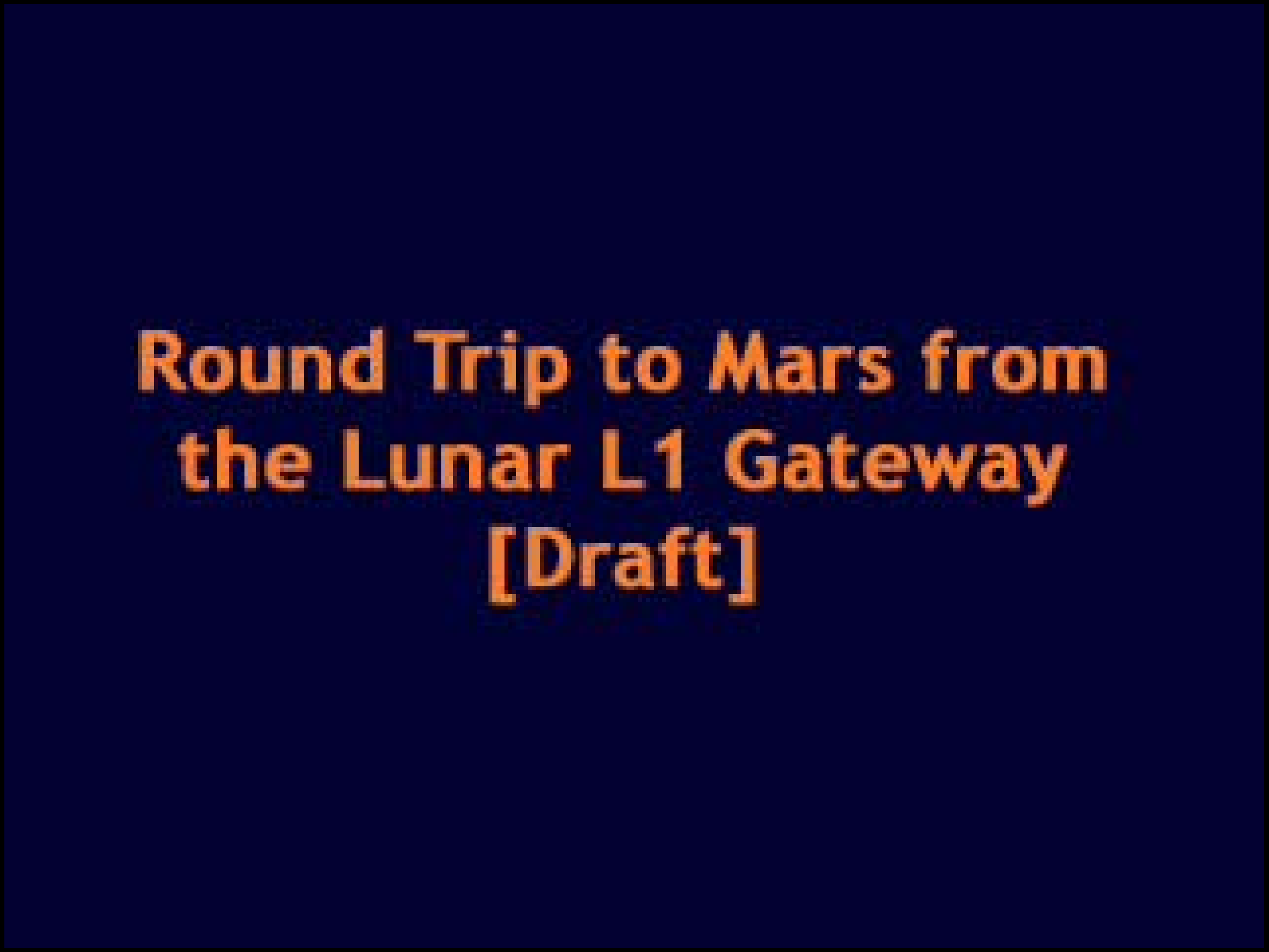
Bring Near-Earth Asteroids to Lunar L1 Using IPS

- ***Asteroid mining – using space resources***
  - **Semiconducting and precious metals**
  - **Construction materials for large space structures**
    - **for tourism, zero-g manufacturing, solar power generation**
    - **Ref: Sercel, Ross, Parker, McDaniel, Voss [2002]**





Human Rendezvous with Mars



Conclusion

- ***InterPlanetary Superhighway (IPS)***
  - **Natural paths connecting solar system**
  - **Arises from dynamics in three-body problem**
  - **Applications to Space Mission Design**
    - **Petit Grand Tour of Jovian moons**
    - **"Shoot the Moon": cheap capture into lunar orbit**
- ***Lunar L1 Gateway Station***
  - **Low cost to many destinations**
    - **Transportation hub**
    - **Construction & repair of Earth L2 spacecraft**
  - **Bring near-Earth asteroid to Lunar L1 using IPS**
    - **Build large structures, tourism?**

References and Further Information

- ***For more information, see the website:***

  www.cds.caltech.edu/~shane

- ***Papers***

  - **Lo, Ross [2001] The Lunar L1 Gateway: Portal to the Stars and Beyond. *AIAA Space 2001 Conference, Albequerque, New Mexico, USA, 28-30 August.***
  - **Koon, Lo, Marsden, Ross [2001] Low Energy Transfer to the Moon. *Celestial Mechanics and Dynamical Astronomy* 81(1-2), 63-73.**
  - **Koon, Lo, Marsden, Ross [2002] Constructing a low energy transfer between Jovian moons, *Contemporary Mathematics* 292, 124-129.**
  - **Gomez, Koon, Lo, Marsden, Masdemont, Ross [2001] Invariant Manifolds and Material Transport in the Solar System. *AAS/AIAA Astrodynamics Specialist Conference, Quebec City, Canada, 3 July – 2 August* (Paper AAS 01-301).**
  - **Koon, Lo, Marsden, Ross [2000] Heteroclinic Connections between Periodic Orbits and Resonance Transitions in Celestial Mechanics. *Chaos* 10(2), 427-469.**

Upcoming Conference (June 10-14)

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INTERNATIONAL CONFERENCE ON
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<u>http://europa.ieec.fcr.es/libpoint/main.html</u>