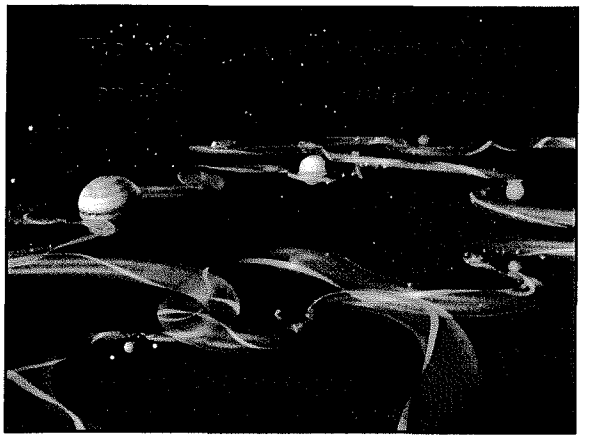


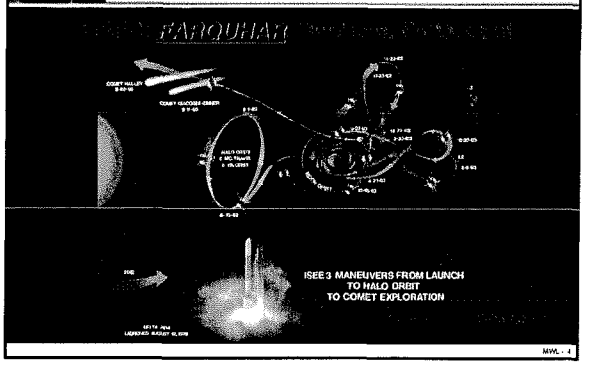
Trajectory Is a Key Space Technology

- Trajectory Is Not a "*DEAD*" Subject
  - Golden Age of Trajectory Technology Just Around Corner
- Trajectory Is a Mission-Enabling, *Intellectual* Technology
  - Not All Technology Is Hardware!
- Space H/W Technology and Trajectory *MUST* Develop Side by Side
  - Like "Rail Road Tracks" for the Train
  - Example: Ion Engines Have Been Around a Long Time, Their Use Have Been Limited by the Lack of 'Low Thrust' Trajectory Design Tools

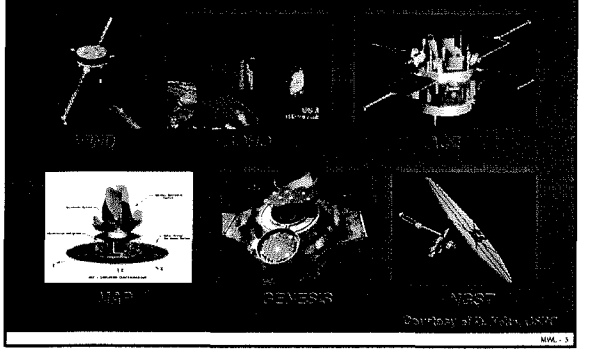
Outline

- The InterPlanetary Superhighway (IPS)
- A New Paradigm for the Solar System
- Low Energy Orbits for Space Missions

How It All Began: ISEE3/ICE

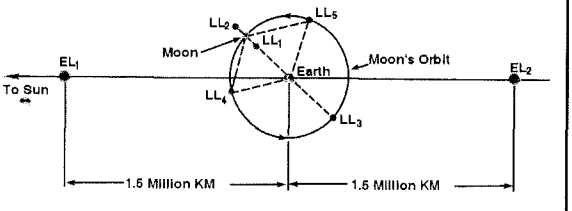


Current Libration Missions

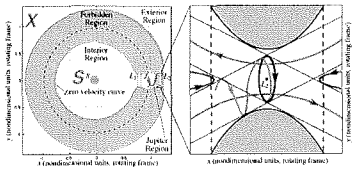


Lagrange Points in Earth's Neighborhood

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



Orbital Zoology Near the Lagrange Points



S: Sun Region

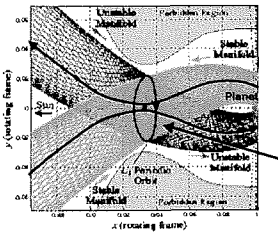
J: Jupiter Region

X: Exterior Region

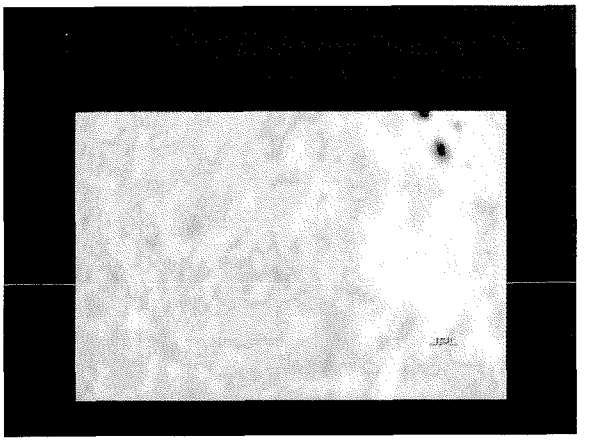
(Outside Jupiter's Orbit)

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

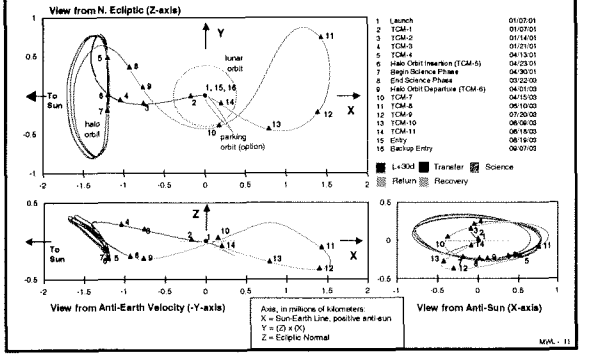
Generated by Stable & Unstable Manifolds of Unstable Libration Orbits



- Unstable Periodic Orbits
  - Generate the Tubes
  - Portals to the Tubes
- The Tubes Govern Transport
  - Transport Must Occur Thru Tubes
  - Systematically Map Out Orbit Space
- Green Tube = Stable Manifold: Orbits Approach the L_1 Periodic Orbit, No ΔV Needed
- Red Tube = Unstable Manifold: Orbits Leave the L_1 Periodic Orbit

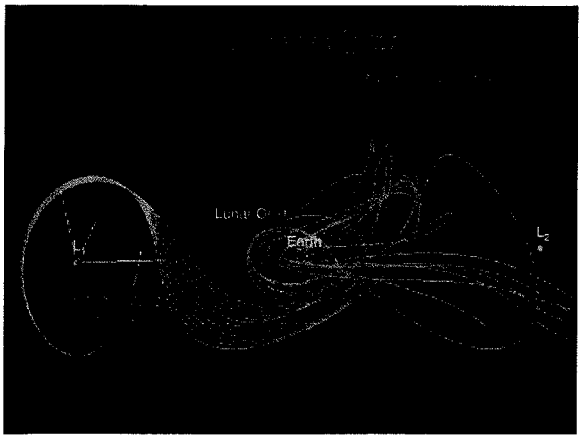


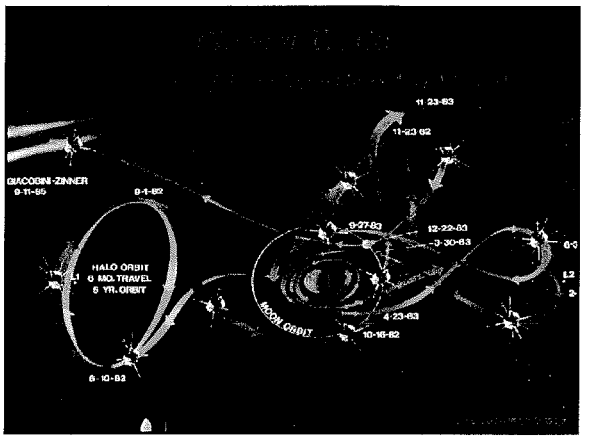
Nominal Trajectory NO Deterministic ΔV!

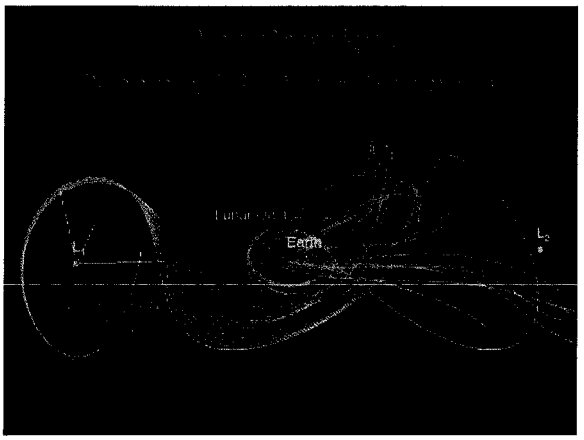


Genesis Mission Design Collaboration

- *Martin Lo* — JPL
  - Genesis Mission Design Manager
- *Kathleen Howell* — Purdue University
  - Department of Aeronautics and Astronautics
- *Brian Barden* — JPL, Purdue University
- *Roby Wilson* — JPL, Purdue University







The InterPlanetary Superhighway Martin.Lo@jpl.nasa.gov

Why Dynamical Systems Theory?

- Traditional Approach
  - Requires First Hand Numerical Knowledge of Phase Space
  - Each Trajectory Must Be Computed Manually (VERY SLOW)
  - Cannot Perform Extensive Parametric Study or Montecarlo Simulation
  - Optimization Difficult, Nearly Impossible
- Dynamical Systems Theory Provides
  - S/W Automatic Generation of Trajectories
  - S/W Automatically Maps Out Phase Space Structures
  - Near Optimum Trajectory
  - Automatable Parametric Studies & Montecarlo Simulations

ISEE3/ICE Orbit

Genesis Unstable Manifold

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LTool Reduced Genesis End-to-End Orbit Design from 8-12 Weeks to 1 Day

Trade Parameters	LTool Funding Level Options			
Total Cost (Millions of Dollars)	**0**	**1.72 M**	**2.3 M Genesis Critical**	**3.4 M Multi-Mission Critical**
Tool Cost	0	1 M	2.3 M	3.4 M
***Increase Funding* to Genesis Mission Design Workforce**	0	0.72 M (4 WY)	0	0
Genesis Operational Tool at JPL (% at JPL)	50%	75%	100%	100%
Genesis Mission Design Update Turnaround Time	8-12 Weeks	1-2 Week	1 Day	1 Day
Genesis Nominal Mission Design Work (% Planned Work Accomplished)	25%	100%	100%	100%
Genesis Contingency Analysis Work	Current Genesis Mission Design Budget Plan Includes Only Contingency Analysis for Launch Error (< 3 σ)			
Genesis Contingency Analysis Capability	Some < 3 σ	< 3 σ	3 σ	> 3 σ
Genesis Mission Design Risk	High Risk	[illegible]	Low Risk	Low Risk
Multimission Support	Very Limited	[illegible]	Limited	General
Advanced Mission Support Infrastructure	None	None	None	Yes

High Complexity: Tool use requires [illegible] training, process is time-consuming and error-prone.
Low Complexity: Tool enables users to work at higher level, reduces time, error, and complexity.
Very Limited: Provides infrastructure and tools adaptable for future missions with additional funding

We Did It!

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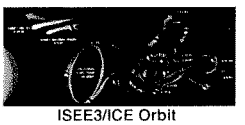
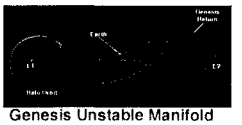
The InterPlanetary Superhighway Martin.Lo@jpl.nasa.gov

LTool Supported Genesis Launch Delay

- Genesis Launch Delayed from 2/01 to 8/01
- LTool Enabled Designers to Replan Genesis Mission in 1 Week
- Without LTool, Genesis Would Require Costly Additional Delay
- LTool and Dynamical Systems Contributed Significantly to Genesis' Successful Launch on 8/8/2001.



ISEE3/ICE Orbit



Genesis Unstable Manifold

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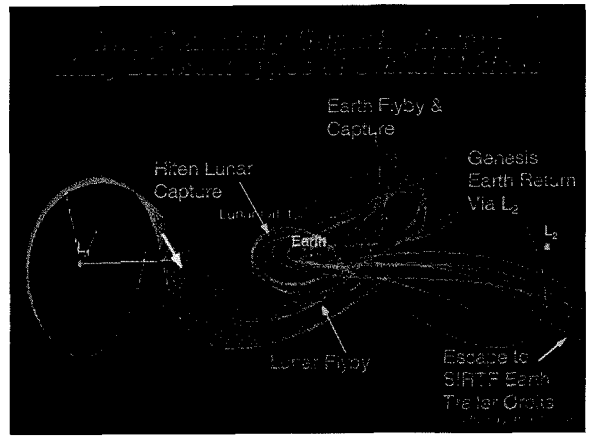
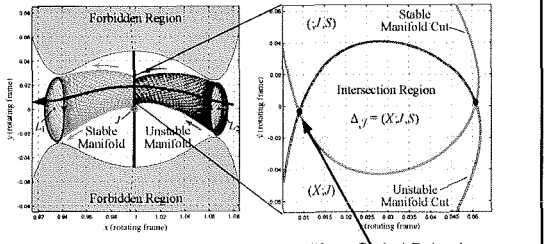
JPL LTool Team

- *Martin Lo* — Section 312
  - Task Manager
- *Dr. Larry Romans* — Section 335
  - Cognizant S/W Engineer (Marthematica Developer)
- *Dr. George Hockney* — Section 367
  - S/W Architecture & Sys Engineer
- *Dr. Brian Barden* — Section 312
  - Trajectory Design & Algorithms
- *Min-Kun Chung* — Section 312
  - Astrodynamics Tools
- *James Evans* — Section 368
  - Infrastructure S/W, Visualization Tools

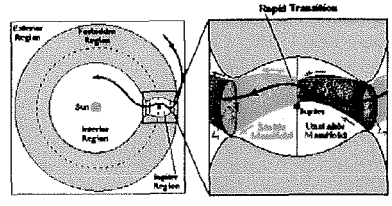


Tunneling Through Phase Space Via IPS



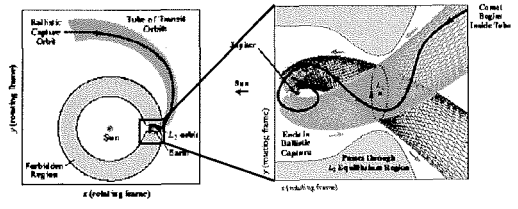
- Cross Section of Tube Intersection Partitions Global Behavior
  - Yellow Region Tunnels Through from X Through J to S Regions
  - Green Circle: J to S Region, Red Circle: X to J Region
  - Genesis-Type Trajectory Between L_2 and L_1 Halo Orbits (Heteroclinic)

Construction of Rapid Transition



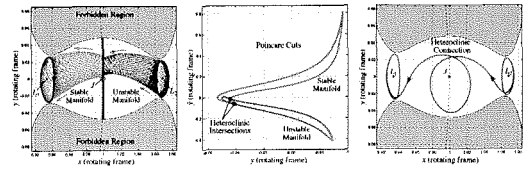
- Manifold Intersections Computed Via Poincare Sections
- Reduce Dimension by 1, Tube Becomes Circle
- Intersections Provide Transit Orbits from L_2 to L_1

Construction of Capture Orbits



- Manifold Intersections Computed Via Poincare Sections
- Reduce Dimension by 1, Tube Becomes Circle

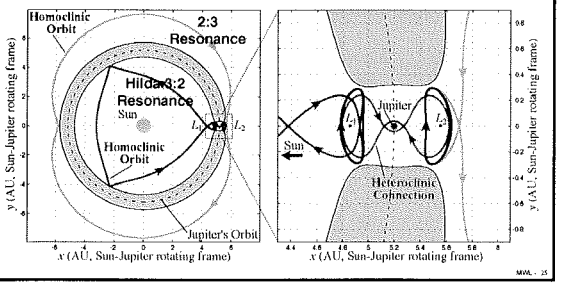
Construction of Heteroclinic Orbits



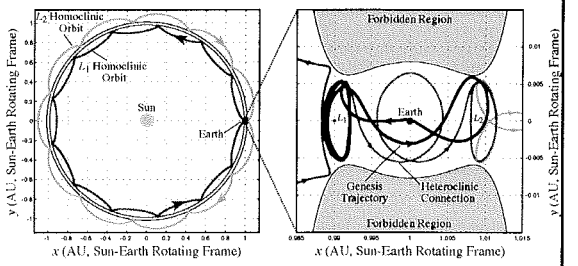
- Manifold Intersections Computed Via Poincare Sections
- Reduce Dimension by 1, Tube Becomes Circle
  - Green Circle Leaves J to S Region
  - Red Circle Enters J from X Region
- Intersections Provide Transit Orbits from L_2 to L_1

Heteroclinic-Homoclinic Chain in Jupiter's InterPlanetary Superhighway

- 2:3 to 3:2 Resonance Transport, No Energy Transfer Needed
- Source of Chaotic Motion in the Solar System



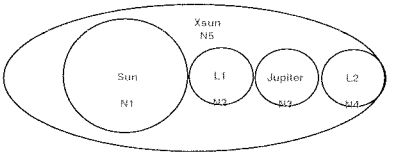
Genesis' Homoclinic-Heteroclinic Chain



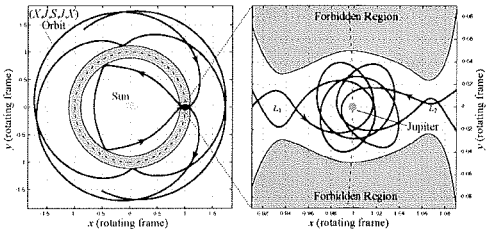
- Genesis Shadows Heteroclinic Cycle, Moon Plays Role (Bell et al.)
- SIRTF, SIM-Type Heliocentric Orbits Related to Homoclinic Orbits

Theorem to Temporary Capture by Design

- The Existence of Homoclinic and Heteroclinic Cycles Implies We Can Choose An Infinite Sequence of Integers, Doubly Indexed,
  N(i ,j) , i = Sun, L1, Jupiter, L2, Xsun; j = 1, 2, 3, ...
  N(i ,j) = Number of Revolutions Around Body(i), Called an ITINERARY
- THEOREM: There Exist an Orbit Which Realizes N(i ,j).
- Based on Conley-Moser's Theorem on Symbolic Dynamics
- *Voila! TEMPORARY CAPTURE BY DESIGN*



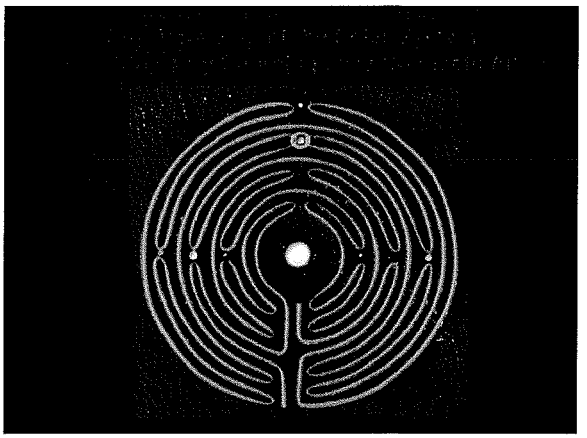
Orbit with Itinerary (X,J;S,J,X)



- Using Symbolic Dynamics Technique to Realize Complex Itinerary
- Capture Around Jupiter Multiple Revolutions (Specifiable)
- Note (2:3) to (3:2) Resonance Transition

Foundation Dynamics Work

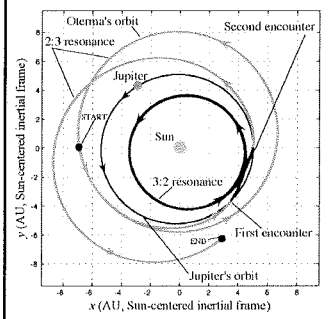
- *Wang Sang Koon* Caltech
- *Martin Lo* JPL, Principal Investigator
- *Jerrold Marsden* Caltech
  - Control and Dynamical Systems Department
- *Shane Ross* Caltech



IPS a New Pardigm of the Solar System

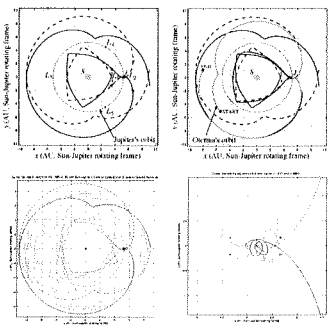
- InterPlanetary Superhighway Connects Entire Solar System
  - Instead of Planets In Isolated Separate Conic Orbits
  - Solar System Is An Organic and Integrated Whole Where Each Part Is Communicating with One Another
  - Governs Transport and Morphology of Materials
- Shape Morphology of Rings and Belts
- Contributes to Theory of Motions of Comets, Asteroids, Dust
- Governs Planetary Impacts from Asteroids and Comets
  - ShoemakerLevy9 Follwed Jupiter IPS to Final Impacts
  - Genesis Trajectory Is an Impact Trajectory
  - 1% of Near Earth Objects In Energy Regime of Genesis Trajectory, Considered Most Danerous
- This Theory Contributes to Understanding of our Origins

Examples from Nature: Comet Oterma



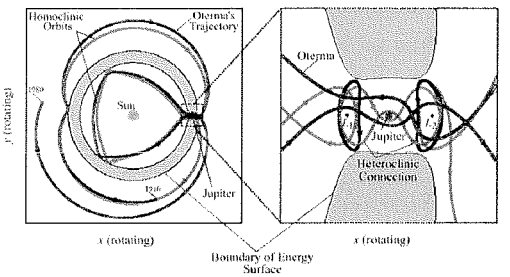
- Theme: Use Natural Dynamics to Optimize ΔV for Space Missions:
  - Genesis 6 m/s Det. ΔV
- Jupiter Family Comets
- (2:3) to (3:2) Free Resonance Transition
- Temporary Capture
- L_1, L_2 as Gate Keeper
- What Is Source of Chaotic Dynamics?

L_1, L_2 Manifolds and Comet Orbits

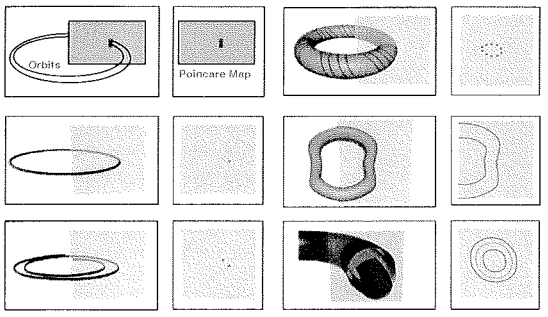


- L_1, L_2 Manifolds Have (2:3) to (3:2) Resonance Transitions
- Manifolds Match Oterma's Orbit Well
- Also Matches Gehrels3 Orbits
  - Temporary Capture
  - Near Halo Orbit
- L_1, L_2 Manifolds Are DNA of This Dynamics
- Need to Study Invariant Manifold Sturcture

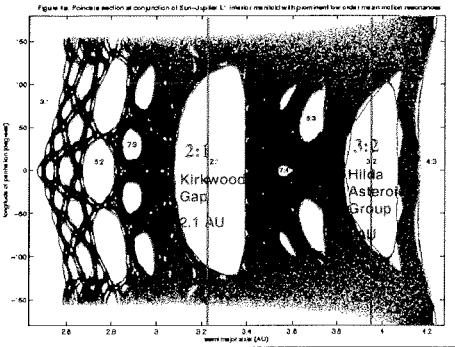
Comet Oterma Shadows Jupiter's Heteroclinic-Homoclinic Cycles



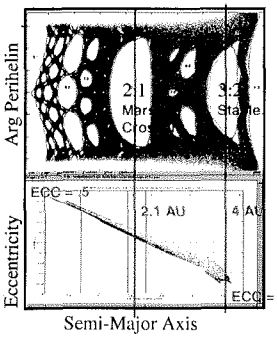
Mapping the Orbit Space Using Poincare Sections



Poincare Section of Jupiter's IPS



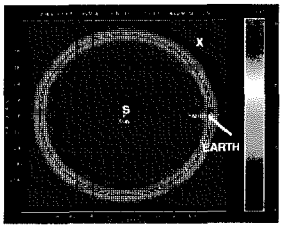
Asteroid Belt Stucture Induced by IPS



- Poincare Section from Single Orbit Leaving Jupiter L1
  - Each Dot Is a Rev Around the Sun
  - Spirals Towards Inner Solar System
  - Eccentricity Grows
- Indistiguishable from Ordinary Conic Orbits
- Controls Asteroid Belt Structures
- Controls Dust Transport and Morphology
- Intimate Connection with Low Thrust Trajectory Design

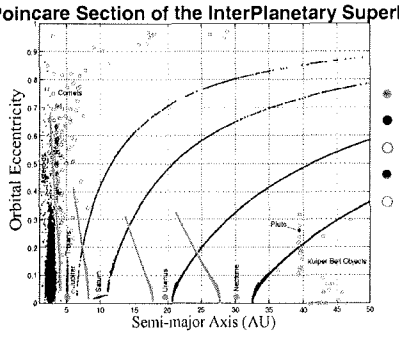
IPS ExoZodi Dust Signatures for Planet Detection

- Earth's Zodi Dust Ring Simulated With Lagrange Point Dynamics
  - Only Gravity, No PR Drag
- S: Sun Region, Earth: Planet Region, X: Exterior Region
- May Provide Planetary Signatures for Exo-Planet Detection



IPS and Transport in the Solar System

Poincare Section of the InterPlanetary Superhighway

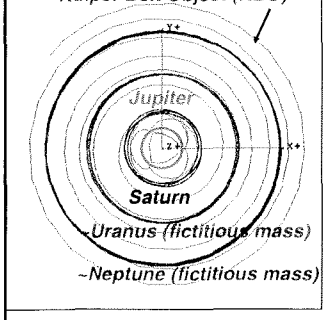


Legend
- L_1 IPS Orbits
- L_2 IPS Orbits
- Comets
- Asteroids
- Kuiper Belt Object

Discovery of InterPlanetary Superhighway

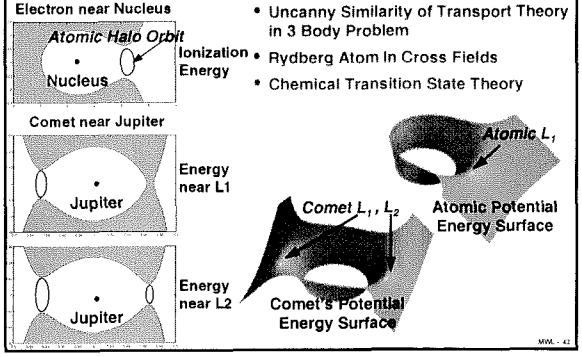
- *Martin Lo* JPL
  - Genesis Mission Design Manager
- *Shane Ross* Caltech
  - Control and Dynamical Systems

Around the Solar System in 80K Days



- *FREE* Spiral Orbit Transfer of KBO to Asteroid Belt Produced by LTool Using IPS
  - Origin of Jupiter Comets
  - Replenish Asteroid Belt
  - Escape from Solar System
- Less Than 1 Pluto Year
- Scales for Jupiter and Saturn Satellite Systems
- Suggests New Low Thrust Algorithm

From AU to au: Comets & Atomic Physics



- Uncanny Similarity of Transport Theory in 3 Body Problem
- Rydberg Atom In Cross Fields
- Chemical Transition State Theory

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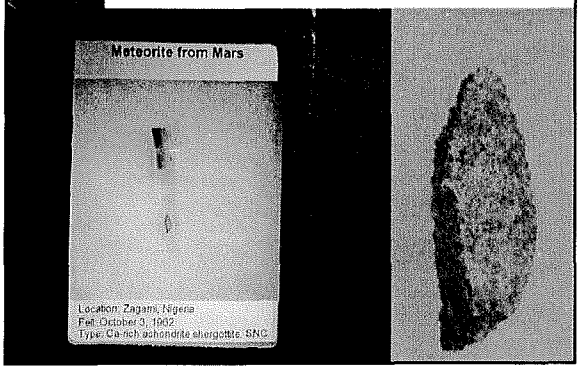
Mars Meteorite



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*Asteroid Transport Rate Near Mars**

- *Charles Jaffe* — West Virgina University
- *Shane Ross* — Caltech
- *David Farelly* — Utah State University
- *Martin Lo* — JPL
- *Jerrold Marsden* — Caltech
- *Turgay Uzer* — Georgia Tech

* To appear in "Physical Review Letters"

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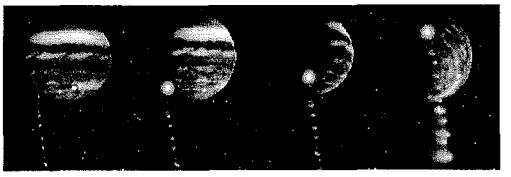
SL9 Impact Via Jovian IPS



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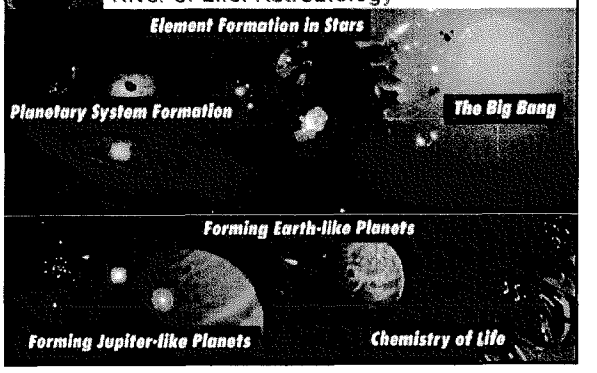
River of Life: Astrobiology



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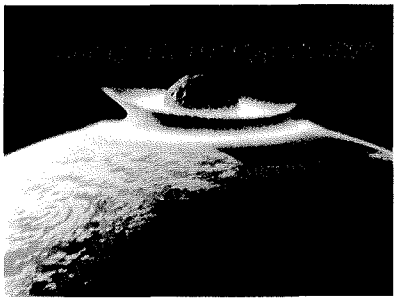
1% Near Earth Objects Have IPS Energies



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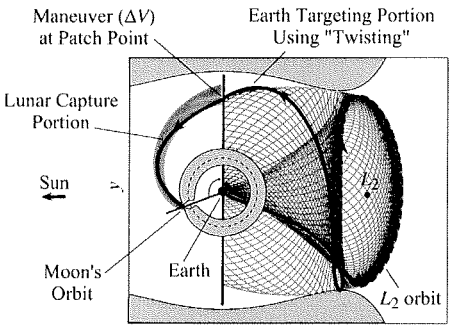
IPS and Development of Life: Exobiology

- InterPlanetary Superhighway Brought Life Building Material from Comets and Asteroids to Earth
- InetrPlanetary Superhighway May Have Brought the Asteroid Killing the Dinosaurs Via a Genesis-Like Orbit
  - Presence of Abundant Iridium Implies Slow Impact Velocity
  - Conjectured by Mike Mueller et al (Nemesis Star)
- InterPlnaetary Superhighway Theory Can Provide Critical Transport Rates for Astrobiology
  - How Rates Determine Formation of Life on a Planet
  - Can Rates Be Obtained from ExoZodi Signatures to Find Potential Life Bearing ExoPlanets?

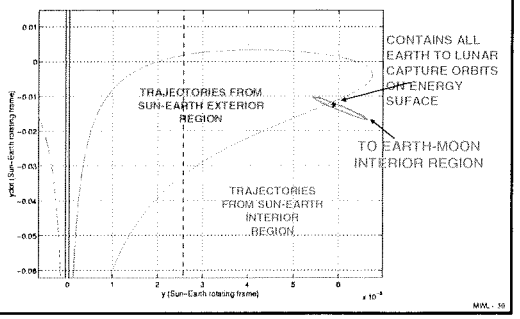
MWL - 48

Dynamics of Hiten Lunar Capture Orbits

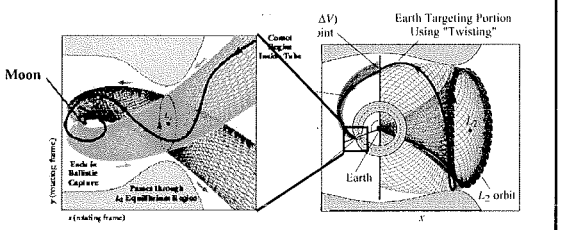


Designing a Lunar Capture Orbit

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

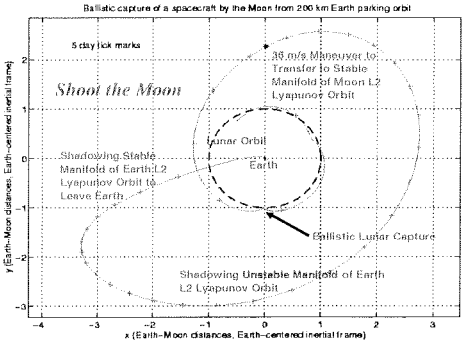


Construction of Capture Orbits



- Manifold Intersections Computed Via Poincare Sections
- Reduce Dimension by 1, Tube Becomes Circle

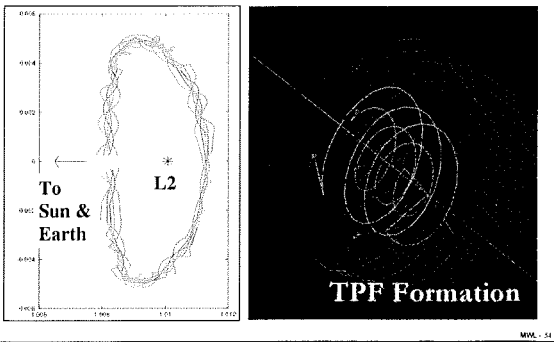
Hiten-Like Low Energy Transfer & Ballistic Lunar Capture



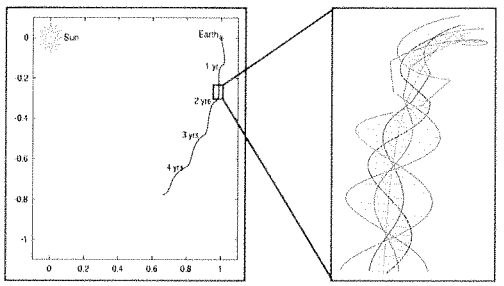
Shoot the Moon: Lunar Capture

- *Wang Sang Koon* Caltech
- *Martin Lo* JPL, Principal Investigator
- *Jerrold Marsden* Caltech
  - Control and Dynamical Systems Department
- *Shane Ross* Caltech

TPF in Formation Flight Near L_2



TPF in SIRTF/SIM-Like Heliocentric Orbit



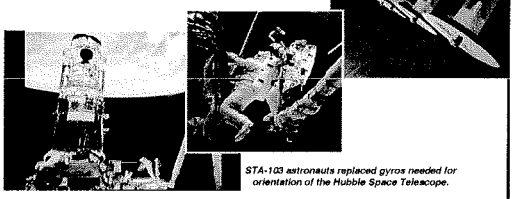
First Formation Flight Design Around L_2

For the Terrestrial Planet Finder Mission (TPF)

- *Min Kun Chung* JPL
- *Gerard Gomez* Barcelona University
- *Martin Lo* *JPL, TPF Mission Design Lead*
- *Josep Masdemont* Polytechnic University of Catalunya
- *Ken Museth* Caltech Computer Graphics Group
- *Larry Romans* JPL

Problem: Human Service to Libration Missions

- ISSUE: 3 Months Transfers to EL_2 Too Long for Humans
- Short Transfers Too Difficult
- Infrastructure Too Expensive

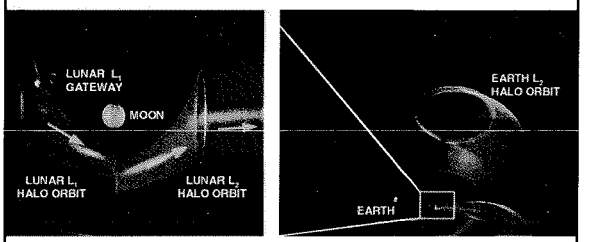


STA-103 astronauts replaced gyros needed for orientation of the Hubble Space Telescope.

JSC

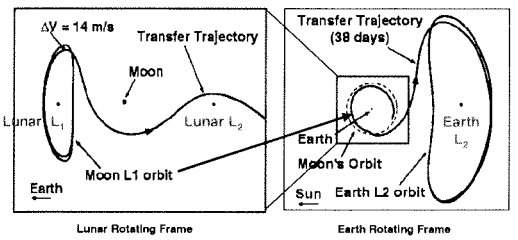
Solution: Human Servicing at Lunar L_1 Gatewy

- Build Instruments & S/C Lunar L_1 Gateway for EL_2
- Service S/C at Earth L_2 from Lunar L_1 Gateway Module



Lunar L_1 to Earth L_2 Transfer

- Build Instruments & S/C Lunar L_1 Station
- Transfer S/C from L_1 to Earth-L_2 LIO (Libration Oribit)
- Service S/C at Earth L_2 LIO from Lunar L_1 Gateway Hub



Servicing Halo Missions at the Lunar L1 Gateway

Round Trip to Mars from
the Lunar L1 Gateway
[Draft]

Lunar L_1 Gateway Human Servicing

Mission Concept Development and Design

- *Martin Lo* JPL, Principal Investigator

Initial Trajectory Design (2D, Coupled RTBP Model)

- *Shane Ross* Caltech

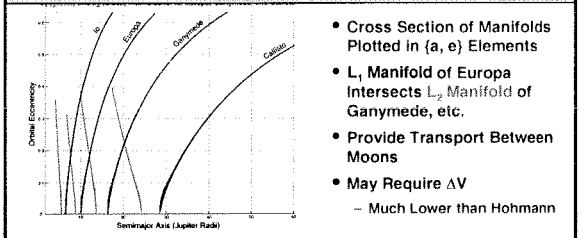
Detailed Trajectory Design (3D, Full Ephemeris Model)

- *Min Kun Chung* JPL

Animation

- *Cici Koenig* Caltech Graphics Group
- *Alan Barr* Caltech Graphics Group

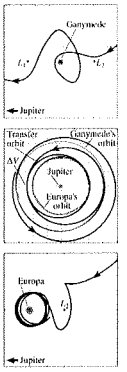
Transport Between Jovian Moons



- Cross Section of Manifolds Plotted in {a, e} Elements
- L_1 Manifold of Europa Intersects L_2 Manifold of Ganymede, etc.
- Provide Transport Between Moons
- May Require ΔV
  - Much Lower than Hohmann

JPL

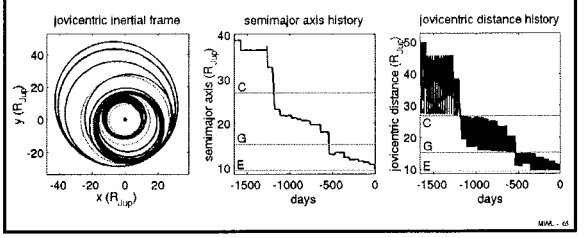
Petit Grand Tour of Jovian Moons



- Mission Concept
  - Flexible Itinerary, Visit Jovian Moons in Any Order
  - User Low Energy Transfer, Capture, Impact
  - Near Circular Orbits Reduce Jupiter Radiation
- Proof of Concept Point Design Using the Interplanetary Superhighway
  - 25 Day Transfer from Ganymede to Europa
  - Requires DV of 1452 m/s!
  - Compare to Hohmann Transfer of 2822 m/s!
- Free Capture by Europa for 4 Orbits (More Possible)
  - Tour Also Available for Saturn's Moons
  - Applicable to Europa/Titan Orbiter, Lander, & Other Outer Planets Missions

New Frontier: Petit Grand Tour?

- New Computation by My Student Shane Ross
- Serial Visits to Galilean Moons, Final Europa Capture
- Total ΔV ~ 20 m/s! 1500 Days Time of Flight



Shoot the Moon: Lunar Capture

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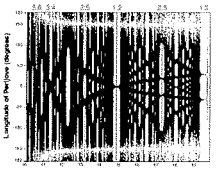
- *Martin Lo* JPL, Principal Investigator
- *Jerrold Marsden* Caltech
  - Control and Dynamical Systems Department
- *Shane Ross* Caltech

New Approach to Low Thrust Orbits

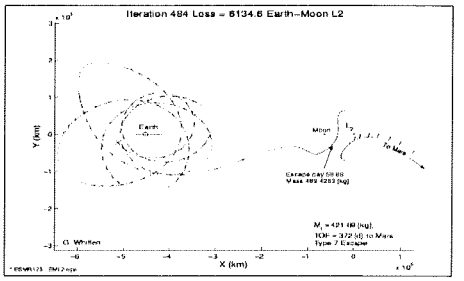
- To Design Low Thrust Orbits, You Must Understand IPS
- Computed from Single Orbit Leaving Europa L2
  - Each Dot Is a Rev Around Jupiter
  - Spirals Towards Europa
  - Eccentricity Grows
- Full of Useful Unstable Orbits
  - Similar to L1/L2 Halo's
  - More Tubes!
- Indistiguishable from Conic Orbits
- New Low Thrust Trajectory Design
  - Use This Transition as First Guess



Europa's IPS

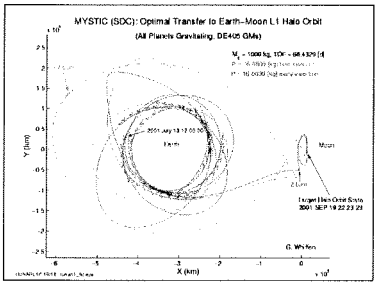
Low Thrust Orbit Naturally Uses IPS!

- Low Thrust Transfer to Mars Via Lunar L1 to L2 Transfer
- Courtesy of G. Whiffen Computed by MYSTIC



Low Thrust to Lunar Gateway L_1 Halo Orbit

- Low Thrust Trajectory Courtesy of G. Whiffen, Computed by MYSTIC
- Halo Orbit Computed by LTool



IPS Technology Road Map

Three Steps: Discover, Understand, Apply

- Map the InterPlanetary Superhighway
  - First Step in Discovery and Exploration
  - Like "Human GENOME", "Star Catalogs", Rand McNally Maps
- Integrate Orbital Dynamics Theories
  - IPS Orbits
  - Continuous Thrust Orbits
  - Conics Orbits
- Develop New Mission Concepts

References

- Barden, Howell, Formation Flying in the Vicinity of Libration Point Orbits, AAS 98-169, Monterey, CA, 2/98
- Barden, Howell, Dynamical Issues Associated with Relative Configurations of Multiple Spacecraft Near the Sun-Earth/Moon L1 Point, AAS 99-450, Girdwood, Alaska, 8/99
- Gomez, Masdemon, Simo, Lissajous Orbits Around Halo Orbits, AAS 97-106, Huntsville, Alabama, 2/97
- Howell, Barden, Lo, Applications of Dynamical Systems Theory to Trajectory Design for a Libration Point Mission, JAS 45(2), April 1997, 161-178
- Howell, Marchand, Lo, The Temporary Capture of Short-Period Jupiter Family Comets from the Perspective of Dynamical Systems, AAS 00-155, Clearwater, FL, 1/2000
- Koon, Lo, Marsden, Ross, Heteroclinic Connections between Lyapunov Orbits and Resonance Transitions in Celestial Mechanics, to appear in Chaos

References

- Koon, Lo, Marsden, Ross, The Genesis Trajectory and Heteroclinic Connections, AAS99-451, Girdwood, Alaska, August, 1999
- Koon, Lo, Marsden, Ross, Shoot the Moon, AAS00-166, Clearwater, Florida, January, 2000
- Lo, The InterPlanetary Superhighway and the Origins Program, IEEE Aerospace2002 Conference, Big Sky, MT, February, 2002
- Lo et al., Genesis Mission Design, AIAA 98-4468, Boston, MA, August, 1998
- Serban, Koon, Lo, Marsden, Petzold, Ross, Wilson, Halo Orbit Correction Maneuvers Using Optimal Control, submitted to Automatica, April, 2000
- Scheeres, Vinh, Dynamis and Control of Relative Motion in an Unstable Orbit, AIAA Paper 2000-4135, August, 2000