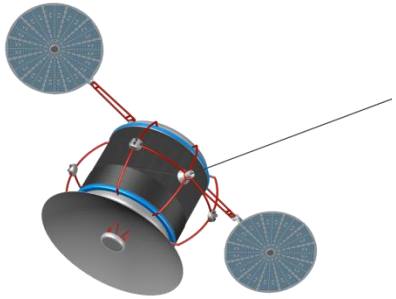
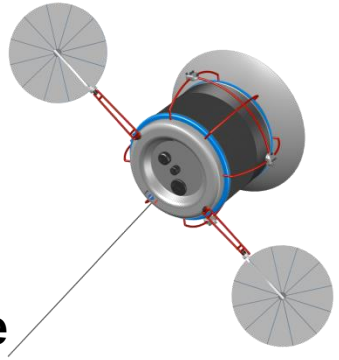
The MAGNETOUR Concept:

Surfing Planetary Systems on Electromagnetic and Multi-Body Gravity Fields

Gregory Lantoine, Rodney Anderson, Hank Garrett, Ira Katz
Jet Propulsion Laboratory, California Institute of Technology

Ryan P. Russell
University of Texas at Austin

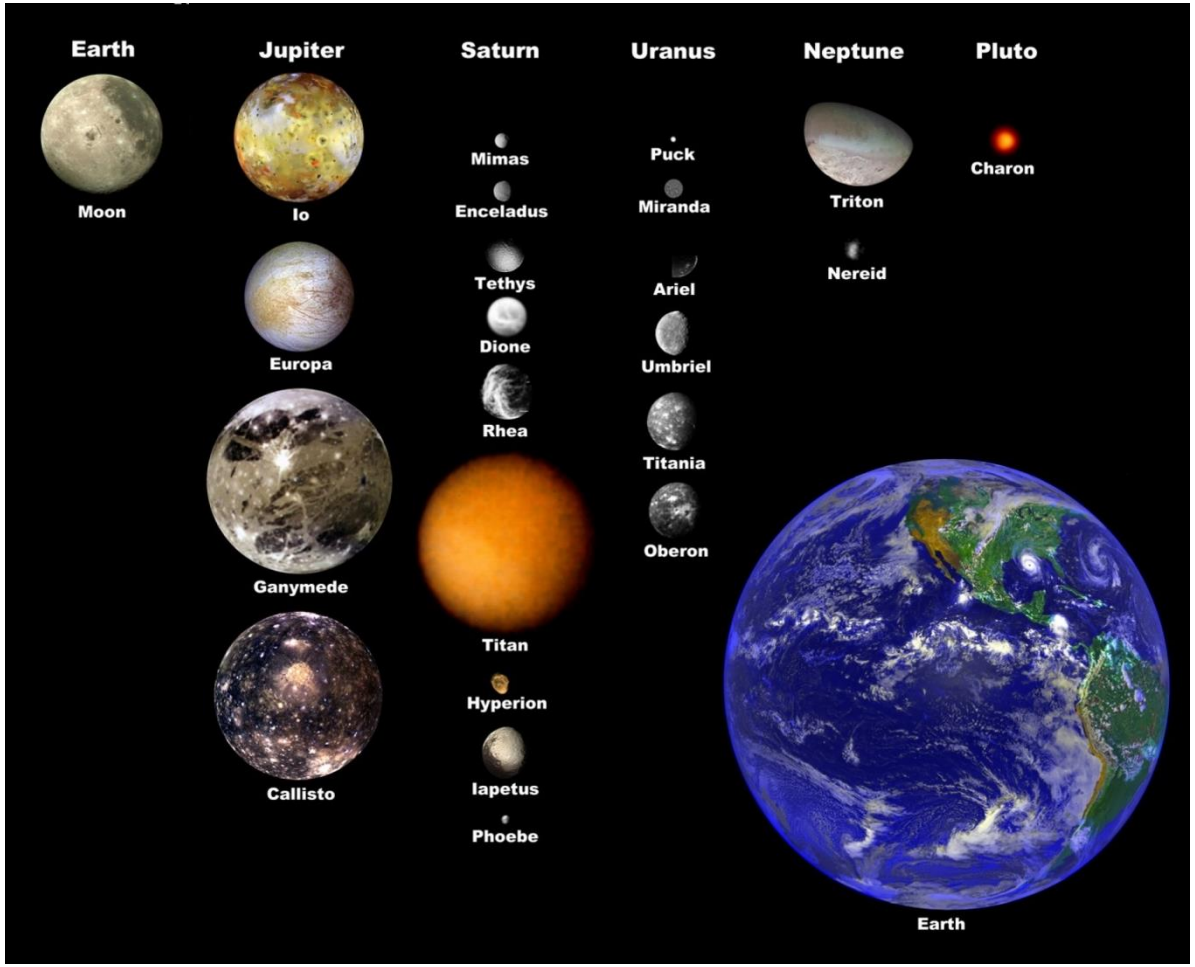




The Fifth International Conference on Tethers in Space
Ann Arbor, Michigan
May 25th 2016

Copyright 2016. All rights reserved.

The Playing Field



Edited from wallpaperhi.com

- Exploring outer planetary systems is a priority of the planetary Decadal Survey

Destinations

Giant Gas Planets
Small Icy Worlds
Intriguing Moons

Science

Interior Secrets
Atmospheres
Extreme Habitats

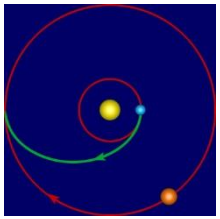
Preference for planetary tour mission

Pre-decisional: for information and discussion purposes only

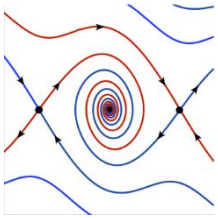
Outer Planet Mission Challenges

Cost

Radiation

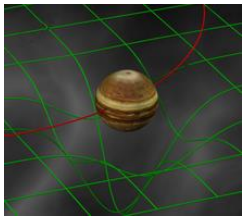


Distance



Chaos

Multiple Targets



Gravity Well

need of new ideas to reduce cost and delta-v of planetary tour missions

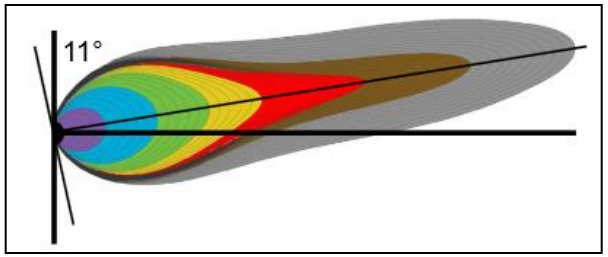
Pre-decisional: for information and discussion purposes only

Outer Planet Environment

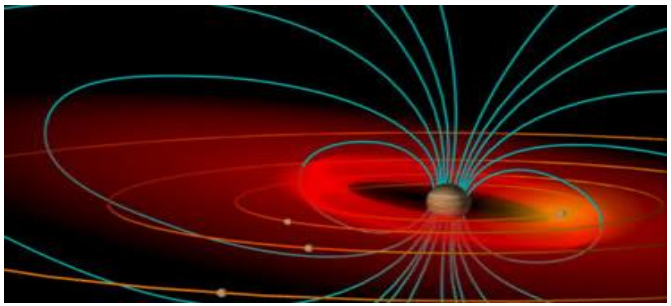
- Multiple moons with significant gravity wells
  - Locked with planet
  - Multi-body dynamics

- Strong magnetic field

Planet	Earth	Jupiter	Saturn	Uranus
Magnetic Moment	1	1.8×10^4	580	50



- Co-rotating plasmasphere
  - Jupiter: mostly from Io
  - Saturn: mostly from Enceladus
  - Uranus: mostly from its atmosphere



Pre-decisional: for information and discussion purposes only

The Basic Idea

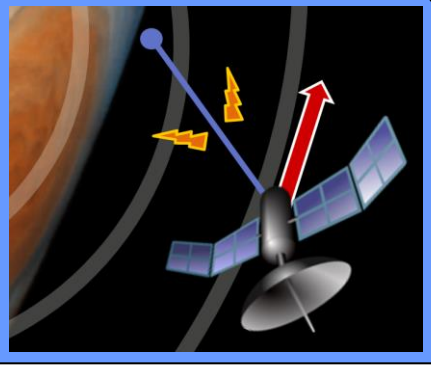
- A spacecraft carrying a conductive tether is subjected to :
  - the gravity forces of the main planet and its moons
  - the electromagnetic (Lorentz) force

1. InterMoon Superhighway

- ✓ Would exploit multi-body dynamics
- ✓ Low-Energy intermoon transfers
- ✓ Existence of weakly captured orbits

2. Electromagnetic propulsion

- ✓ Electrodynamic tether (conductive wire)
- ✓ Would take advantage of magnetic field and plasmasphere
- ✓ Propellantless propulsion and power



MAGNETOUR

Pre-decisional: for information and discussion purposes only

MAGNETOUR Concept

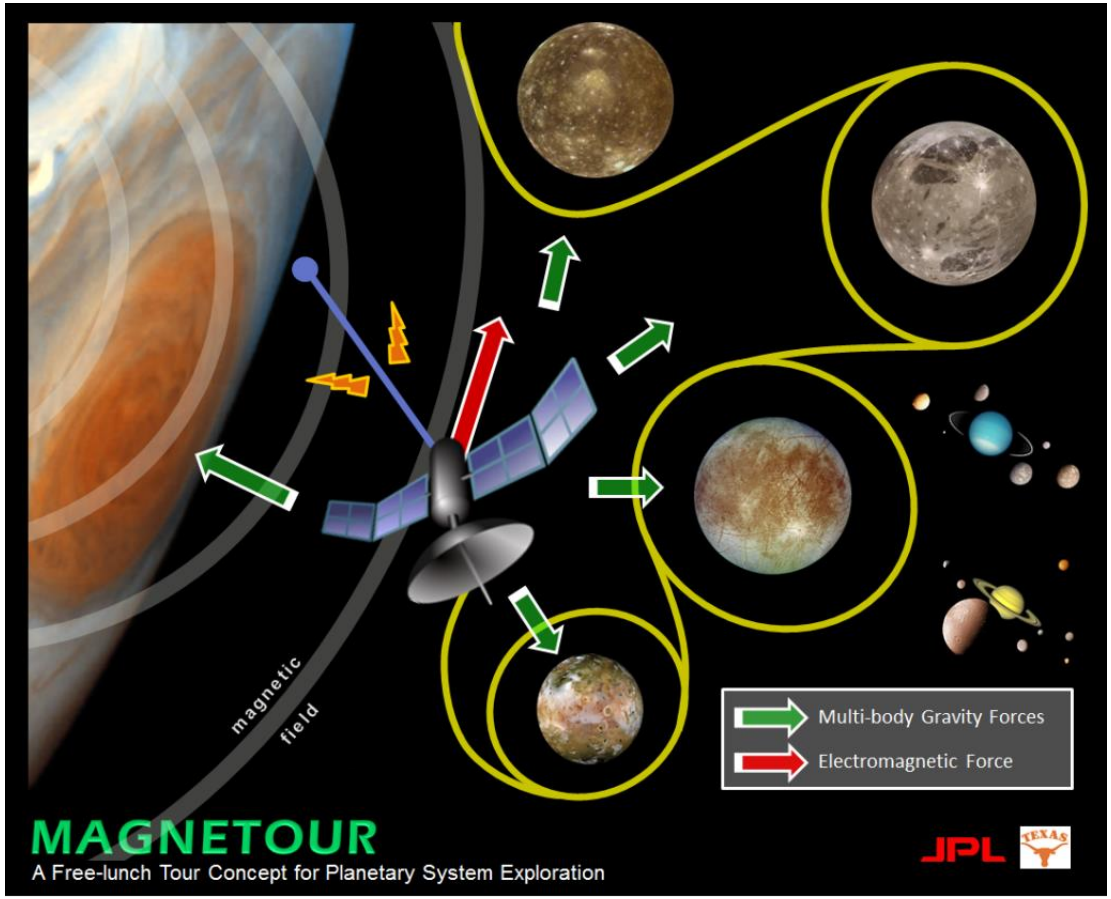
Concept :

- **Quasi-ballistic** moon tour of an outer planet
- Synergic use of **electrodynamic tethers** and gravitational **manifolds** and resonances
- Focus on Jupiter system in this talk

Potential Benefits :

- Propellantless maneuveurs
- On-board power generation
- Increased science payload
- Captured orbits at multiple moons
- Flagship science on low budget
- Agreement with Decadal Survey

The combination of magnetic and multi-body gravity fields could open up innovative, quasi-ballistic trajectories in planetary systems by freely navigating between moons rather than 'fighting' the dynamics



MAGNETOUR mission architecture concept

New paradigm in exploration of planetary systems explored in a 2012 NIAC Phase 1 study

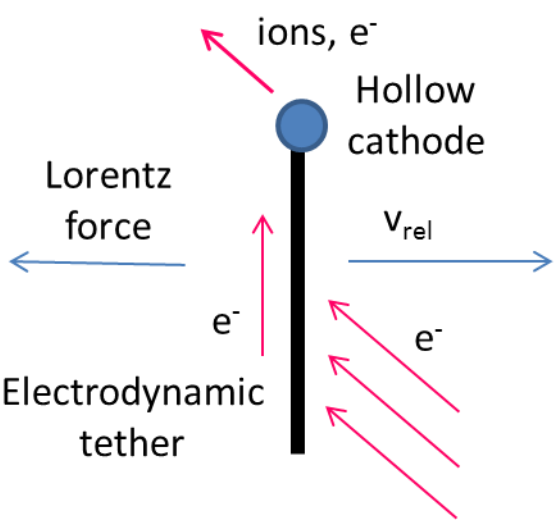
Pre-decisional: for information and discussion purposes only

Electrodynamic Tethers

Pre-decisional: for information and discussion purposes only

Electrodynamic tethers

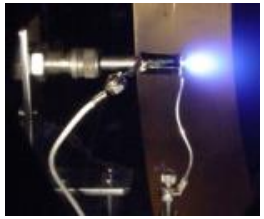
- Electrodynamic tethers are bare conducting wires terminated at one end by an hollow cathode (electron emitter).
- Thrust can be generated through Lorentz-force interactions with a planetary magnetic field.
- Additional thrust can be produced by the hollow cathode itself
- Power can be naturally extracted from the tether



$$\mathbf{F} = L\mathbf{I} \times \mathbf{B}$$

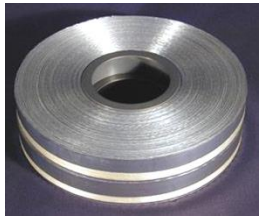
Magnetic field

Electron emitter



Hollow cathode

Electron collector



Credit: Enyuan Co.

Aluminum tape

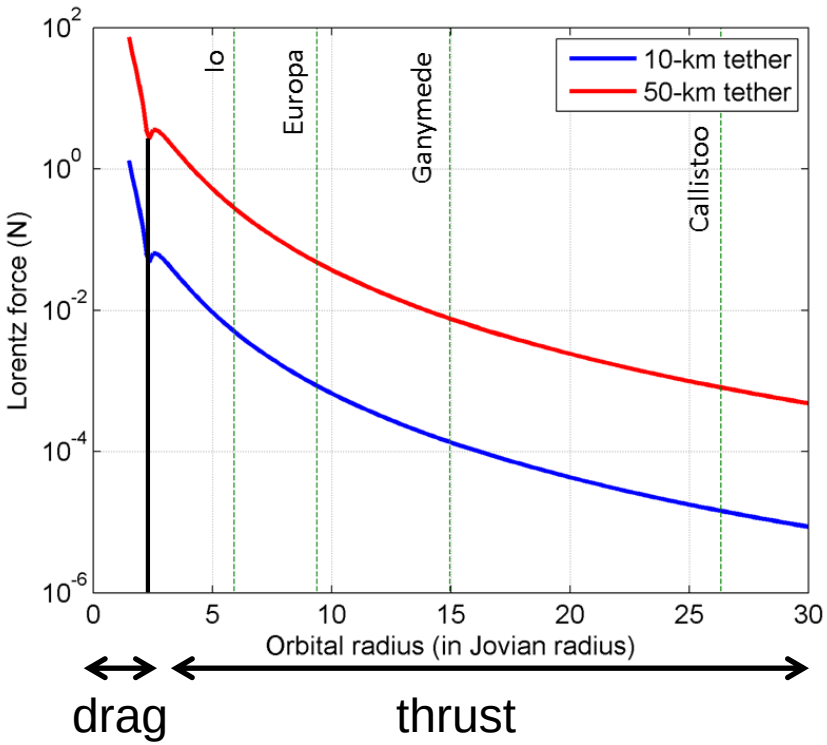
MAGNETOUR uses the electromagnetic Lorentz force as a revolutionary means for propulsion and power during the planetary tour.

Pre-decisional: for information and discussion purposes only

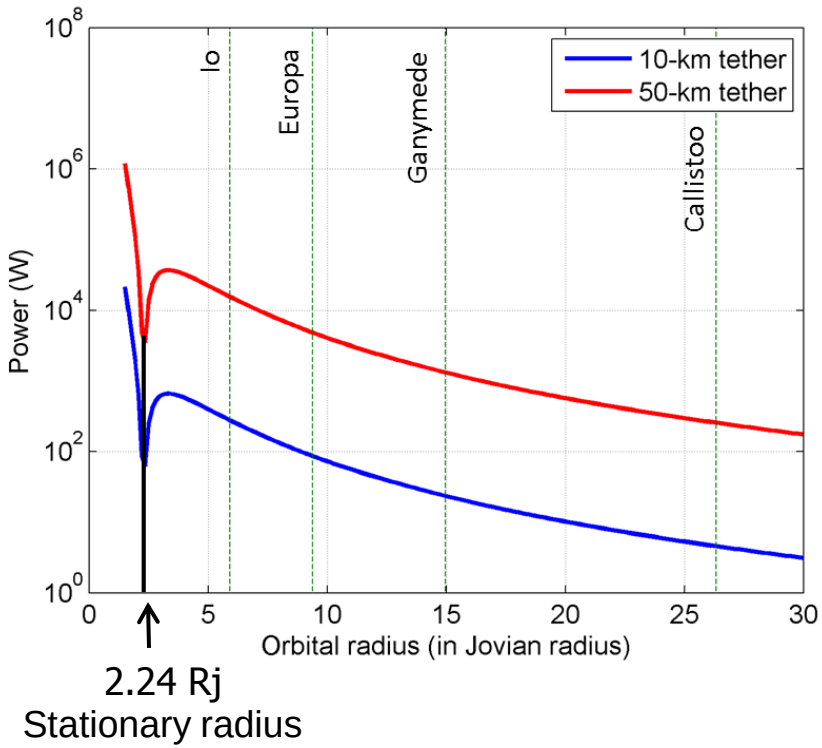
Lorentz Force and Power

- Lorentz force and power produced by electrodynamic tether at Jupiter
  - {Tether + spacecraft} system treated as point mass (simplified model)
  - Magnetic field assumed to be perfect dipole

Lorentz force vs Jovian radius



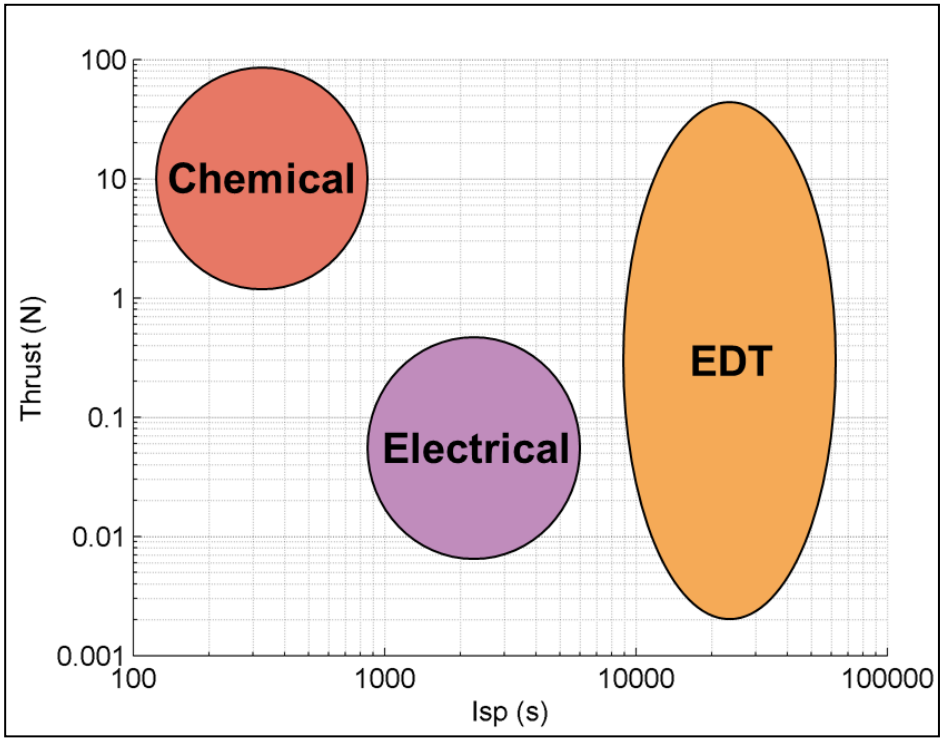
Power vs Jovian radius

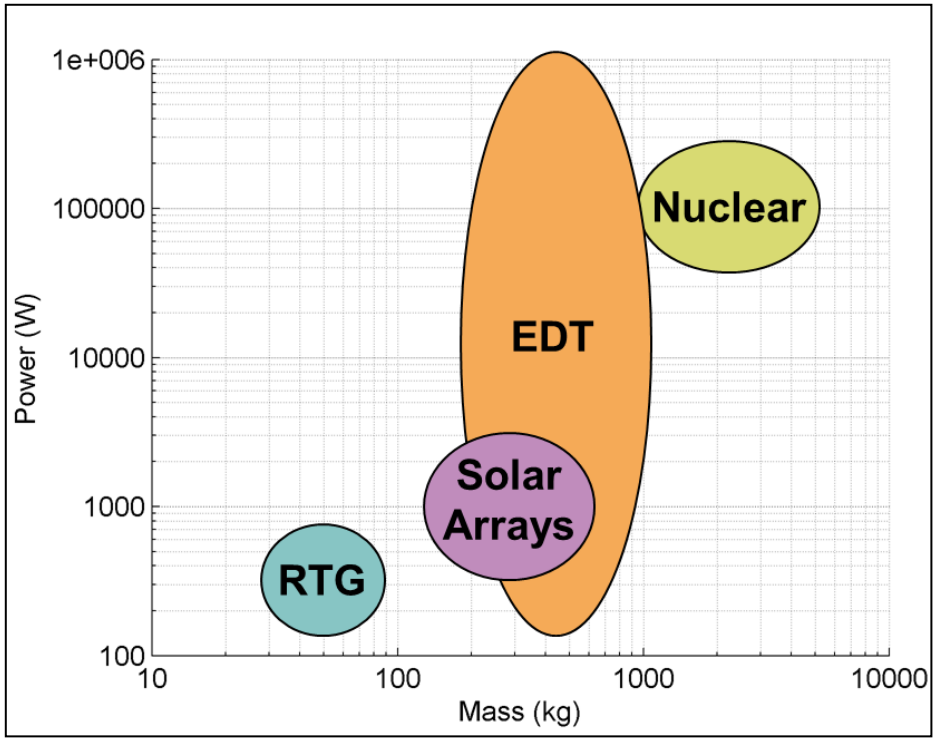


Pre-decisional: for information and discussion purposes only

Propulsion and Power comparisons

- EDTs competitive in both propulsion and power worlds
- Disclaimers:
  - Strong variations with radial distance: short peak thrust and power
  - Limited thrust directions



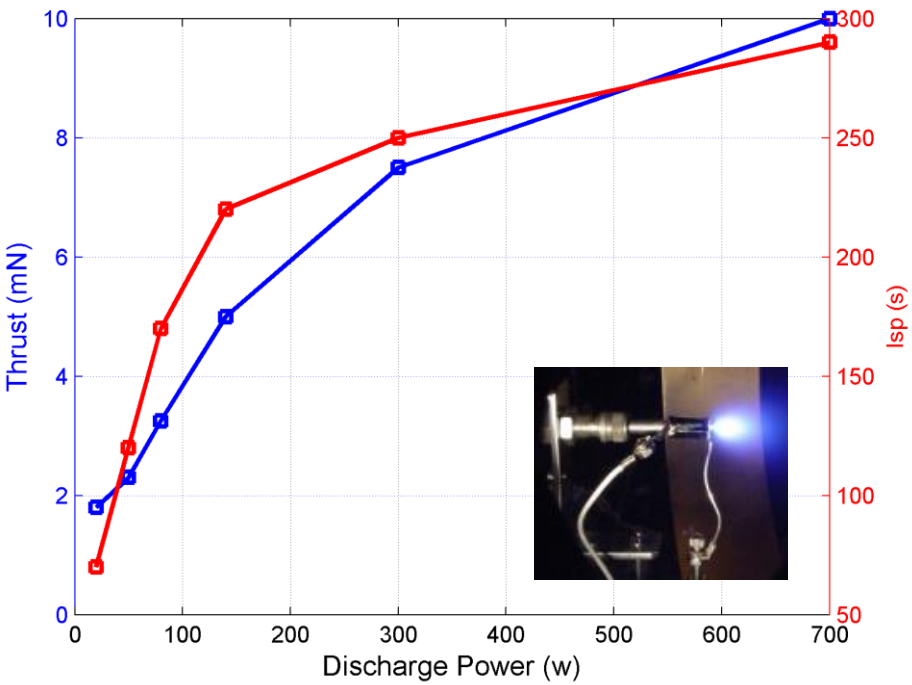


Pre-decisional: for information and discussion purposes only

Hollow Cathode Thruster

- Hollow Cathodes are often used as **electron emitters** with electrodynamic tethers
- Research at JPL shows that standard Hollow Cathodes can also be used as **standalone thrusters**
- Potential use:
  - Attitude control
  - Tether stabilization
  - Complimentary propulsion

Hollow cathode thrust and Isp vs power



A standard hollow cathode can provide up to 10 mN of thrust: it can be used as a standalone mini-thruster !

Pre-decisional: for information and discussion purposes only

Electrostatic tethers

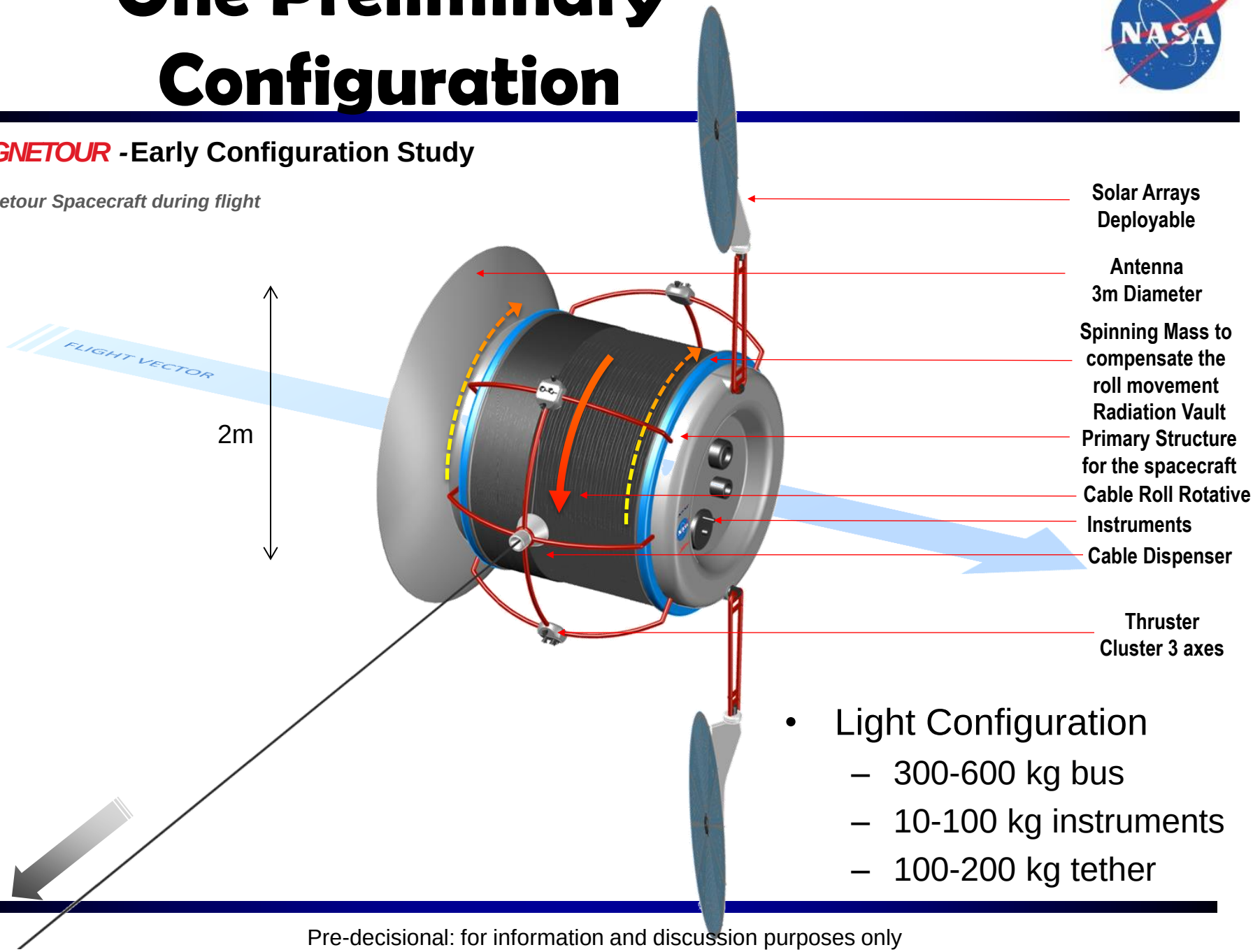
- An electrostatic tether is a promising alternative when the Lorentz force is too small
- Electrostatically repelling the ions of the solar wind using bare wire tethers can be quite efficient. This concept could be exploited both for ions in the solar wind and ions in Jupiter's ionosphere and magnetosphere.
- Dual-mode electrodynamic / electrostatic tether
  - Since both electromagnetic and electrostatic tether propulsion concepts make use of the same bare wire tether hardware, combining the two propulsion schemes could provide spacecraft thrust in regions of space where the ambient magnetic field is small, but the ion flux is large as well as vice versa.

Pre-decisional: for information and discussion purposes only

One Preliminary Configuration

MAGNETOUR - Early Configuration Study

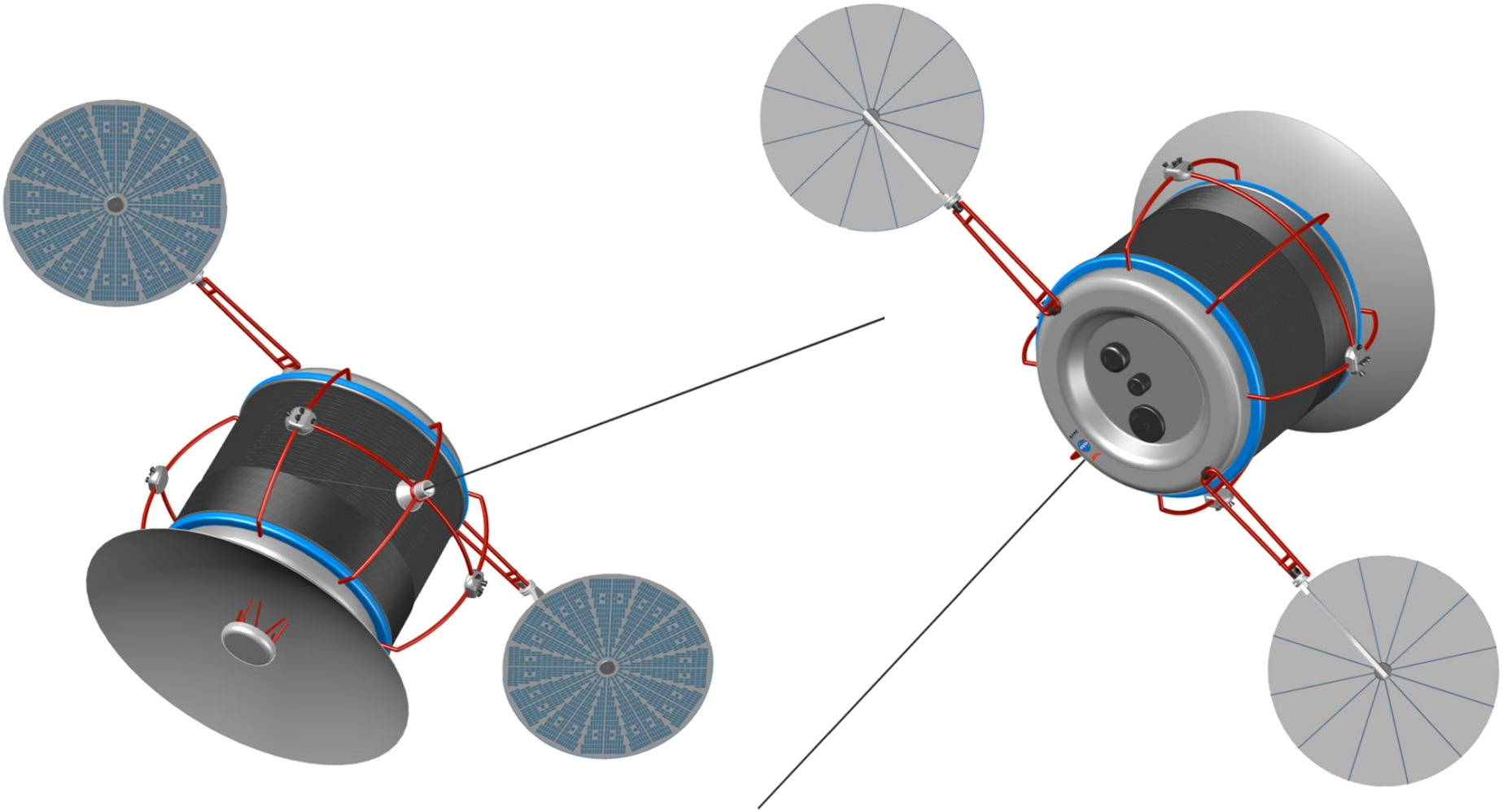
Magnetour Spacecraft during flight



- Light Configuration
  - 300-600 kg bus
  - 10-100 kg instruments
  - 100-200 kg tether

Pre-decisional: for information and discussion purposes only

One Preliminary Configuration



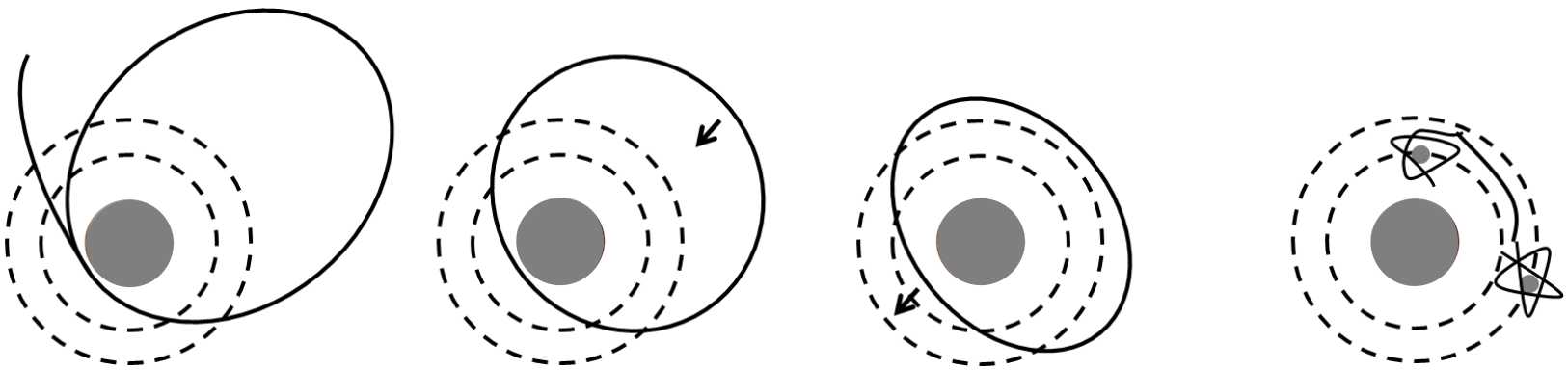
Pre-decisional: for information and discussion purposes only

Jovian Mission Concept Design

Pre-decisional: for information and discussion purposes only

Mission Concept Architecture

- Phases of MAGNETOUR:



1. Capture → 2. Lowering apojove → 3. Raising perijove → 4. Loosely captured orbits and inter-moon transfers

Tether on at perijove (drag)

Tether on at perijove (drag)

Ballistic Flybys

Quasi-ballistic Tour
Tether on for station-keeping

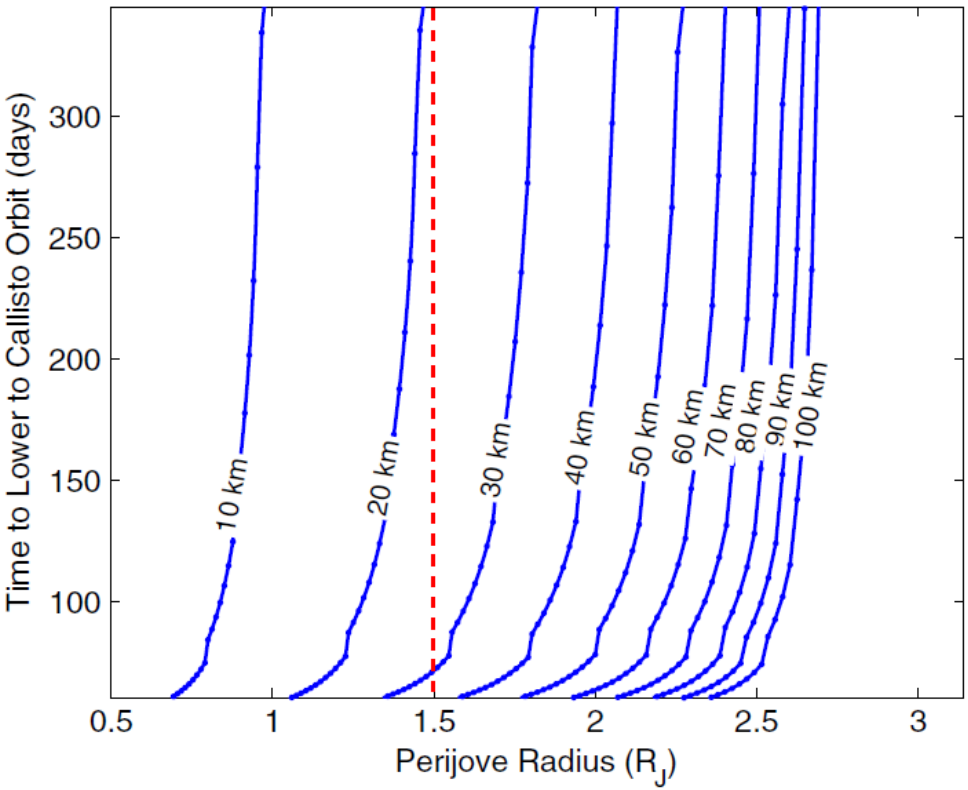
- 25-km tether is a lower bound for capture (1.5 Rj min radius)
- Multiple flybys are needed to raise perijove (use of tether very limited)

Pre-decisional: for information and discussion purposes only

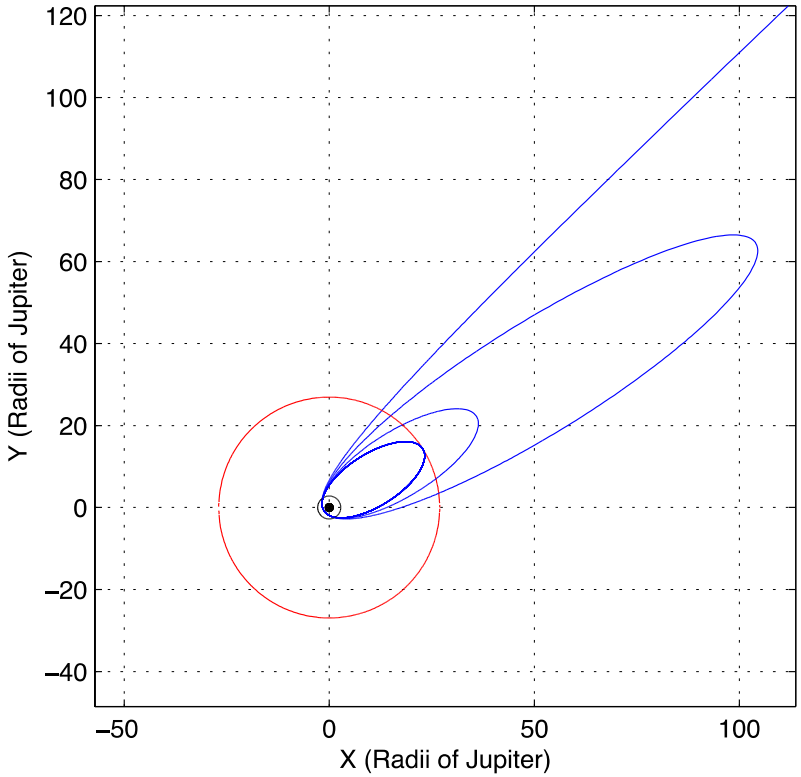
Capture and lowering apojove

- Callisto apojove targeted after successive Jovian perijove passes.
- Minimum length of 25 km for Jovian capture (20 km if flybys of the Jovian moons are allowed)

Time to Lower to Callisto vs Perijove radius for L=10-100km



Capture using L=25km, Rp=1.5*Rj
TOF = 124 days, 3 perijove passes



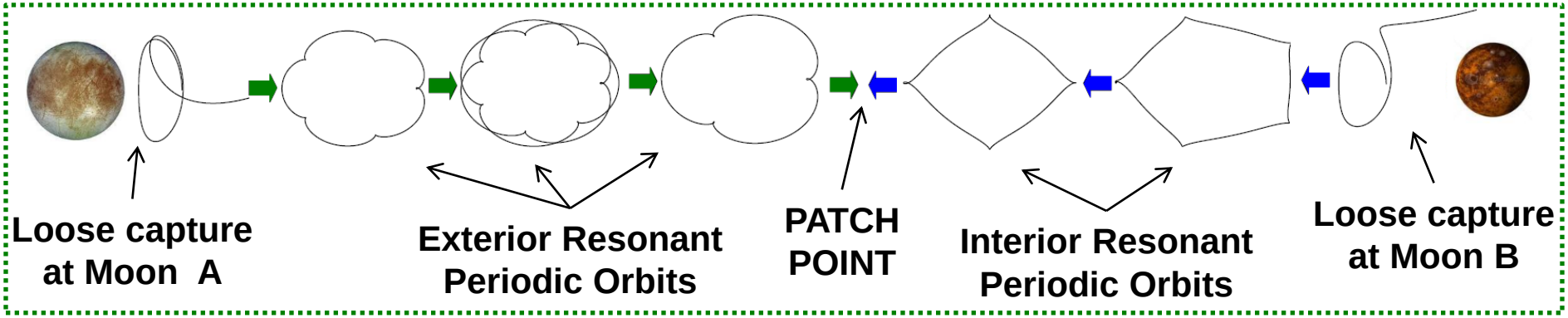
Pre-decisional: for information and discussion purposes only

InterMoon Superhighway Concept

- Goal: quasi-ballistic intermoon transfer and (weakly) captured orbits at each moon

- Navigation of the InterMoon Superhighway
  - Three-body resonant gravity-assists
  - Jump from one resonant orbit to another
  - Weak capture/escape through manifolds

Credit: NASA/JPL

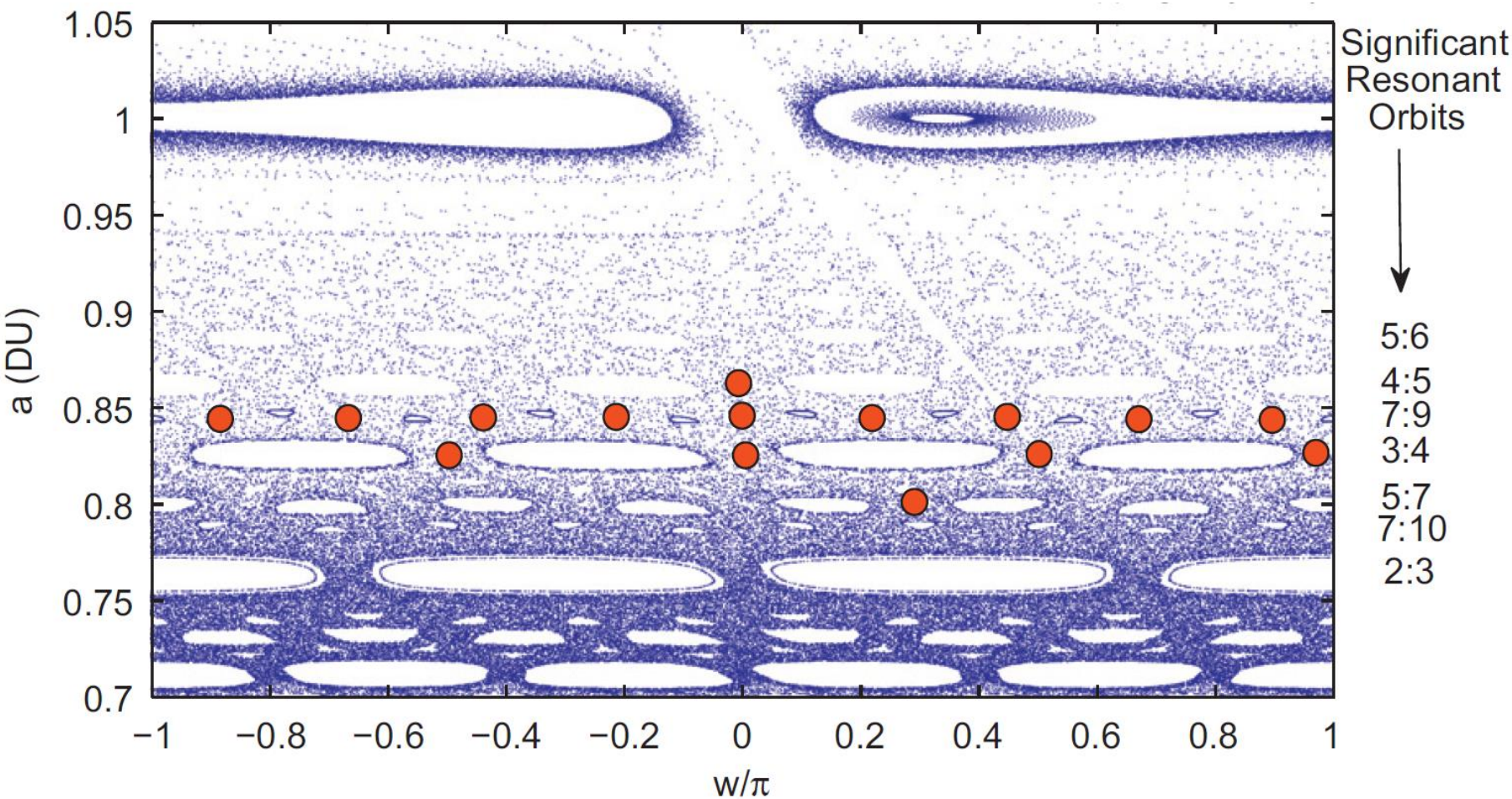


- Extension of the well-known Interplanetary Superhighway
  - Enabling technology for past missions: Genesis, GRAIL, …

Pre-decisional: for information and discussion purposes only

InterMoon Superhighway Concept

- Unstable resonant orbits = waypoints in the chaotic space
- Poincaré Maps to help navigate chaotic three-body design space



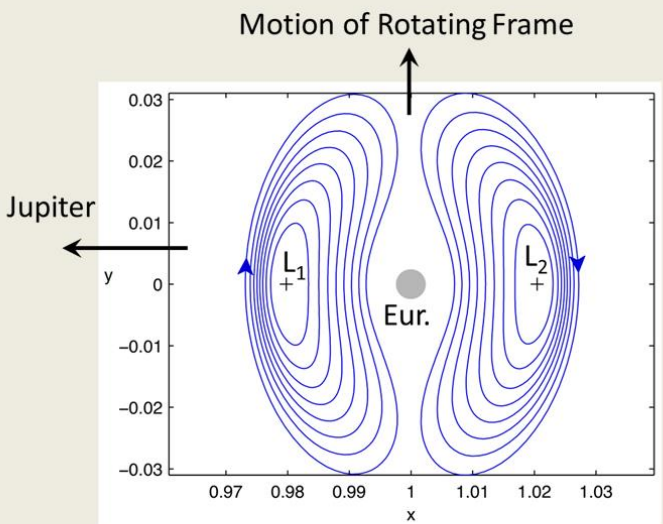
Pre-decisional: for information and discussion purposes only

Lyapunov Orbits

- Classical low altitude science orbits require expensive insertion maneuvers
- The use of third-body loosely captured orbits (such as Lyapunov orbits) can significantly reduce the fuel cost of inserting and orbiting planetary moons

PROPOSED

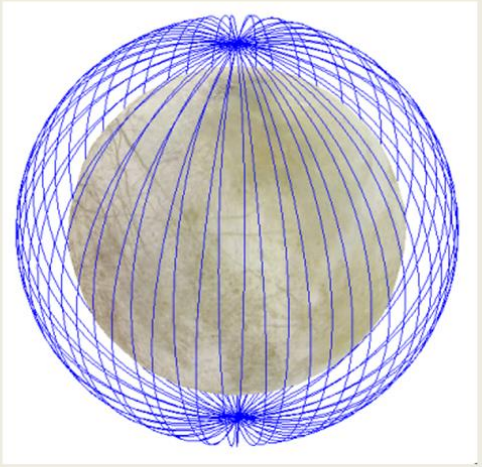
LOOSELY CAPTURED:
shallow in gravity well
low fuel requirements to insert/depart



Lyapunov Orbit Families

CONVENTIONAL

LOW ALTITUDE:
deep in gravity well,
high fuel requirements to insert/depart

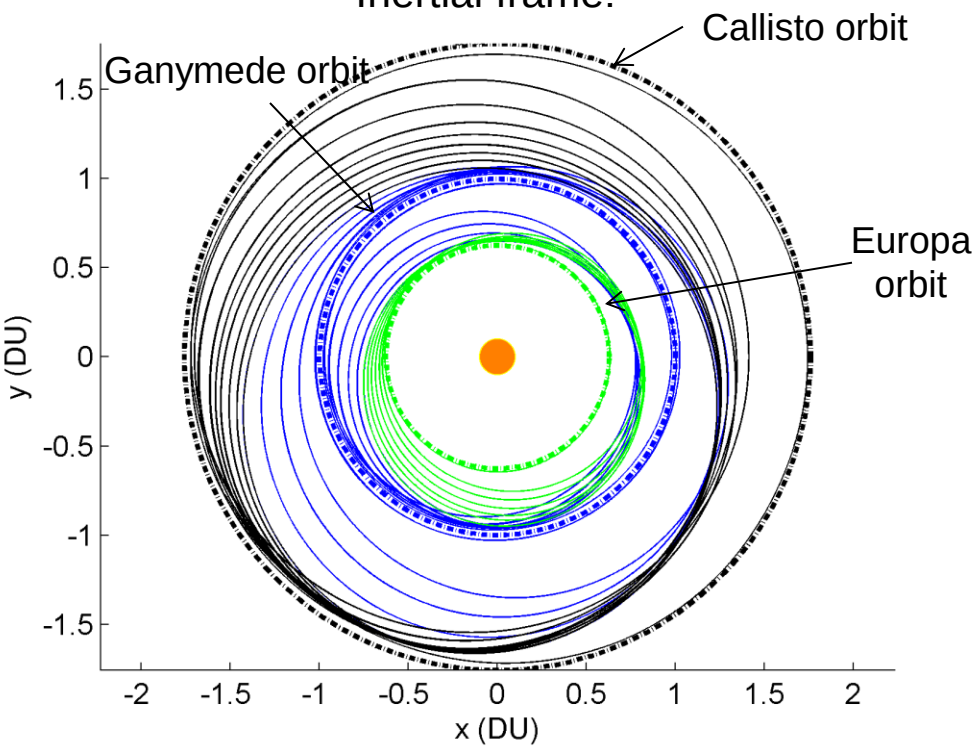


Pre-decisional: for information and discussion purposes only

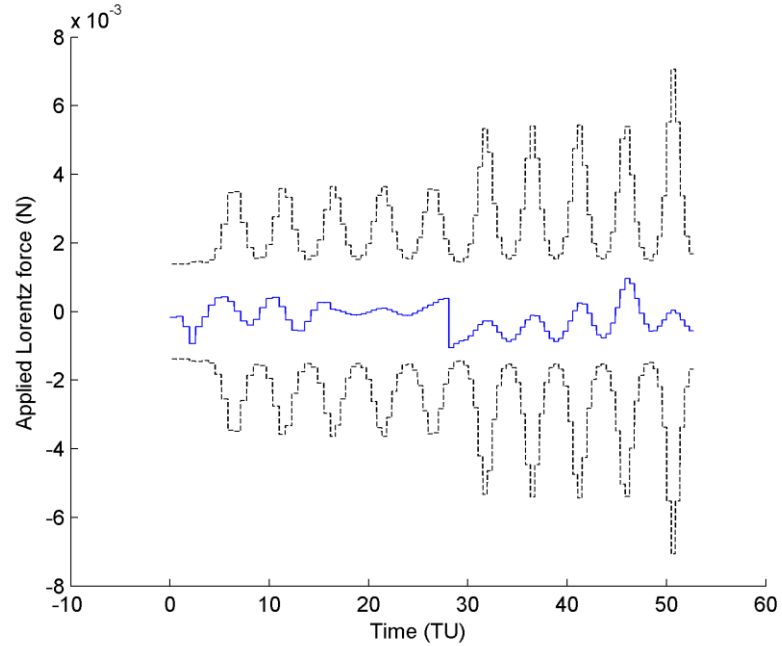
Quasi-Ballistic Multi-Moon Tour Concept

- Quasi-ballistic Jovian tour of Callisto-Ganymede-Europa

Inertial frame:



Lorentz force profile during interior Ganymede-dominated portion. Black dots represent the maximum achievable Lorentz force



Model: Patched Tether-Perturbed Planar Restricted Three-Body Problem

Dark: Callisto dominated
Blue: Ganymede dominated
Green: Europa dominated

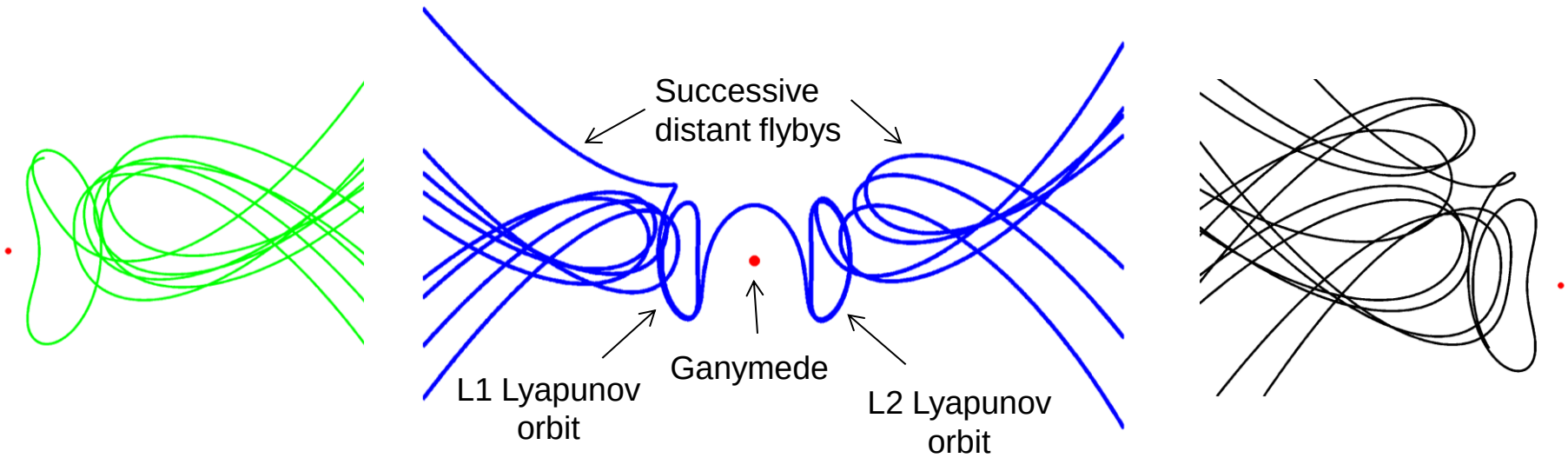
DV = 5 m/s (from tether)

TOF = 1120 days

Pre-decisional: for information and discussion purposes only

Quasi-Ballistic Multi-Moon Tour Concept

Europa Lyapunov L2 ⇦ **Ganymede Lyapunov L2-L1** ⇦ **Callisto Lyapunov L1**



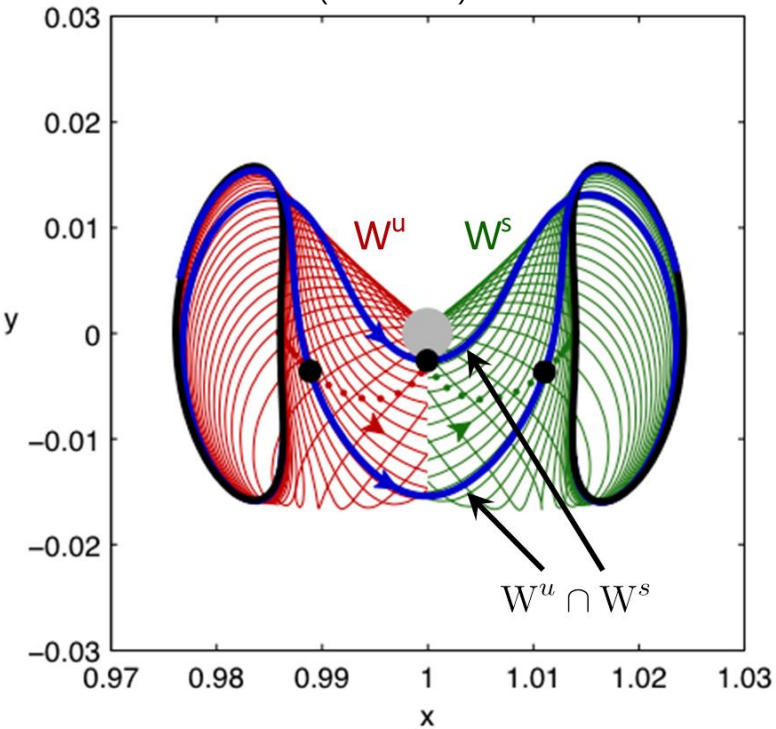
Jupiter-Moon rotating frames

Pre-decisional: for information and discussion purposes only

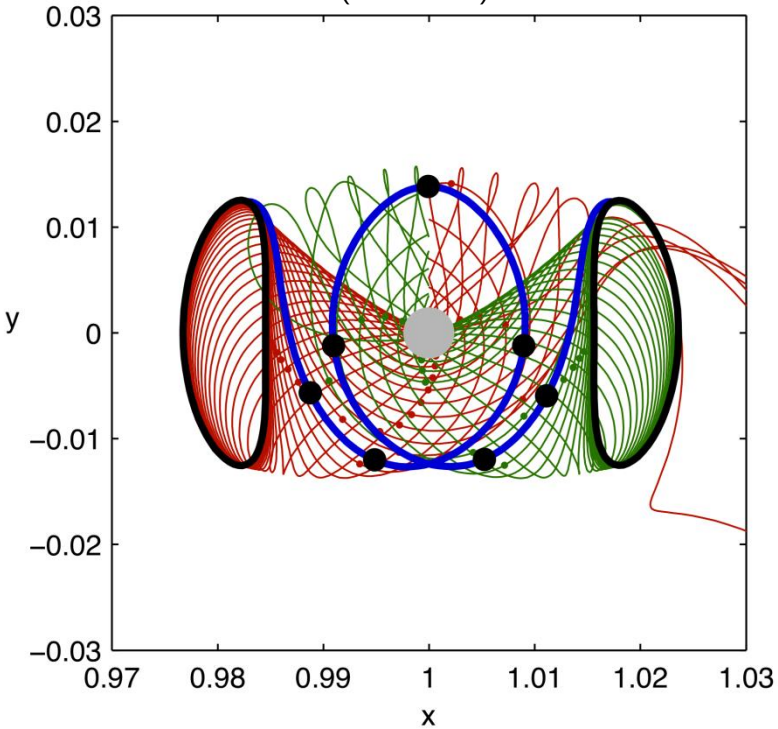
Projected Science Capabilities

- Ballistic heteroclinic connections can get closer approaches of the moons:
  - Free trajectories to go back and forth between Lyapunov L1 and L2 orbits

closest approach altitude = 169.6 km
(C = 3.0028)



heteroclinic connection with multiple flybys
(C = 3.0031)



- Instruments (camera) at the tether tip: better observations during close flybys
- Station-keeping require ΔV ~1e-5 m/s, within tether capability

Pre-decisional: for information and discussion purposes only

Projected Mass Benefits

- Conventional mission

Ex: Europa Orbiter Mission Concept

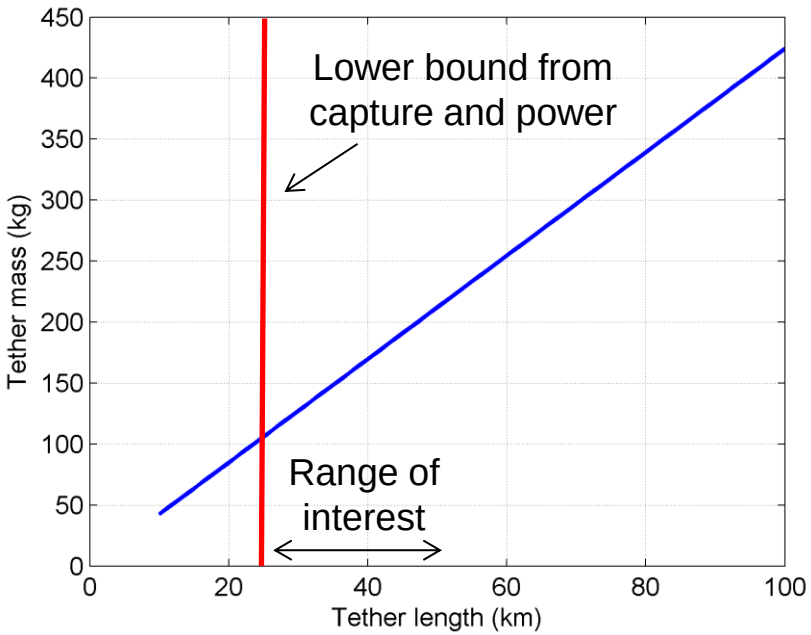
	ΔV *	Propellant
Jupiter Orbit Insertion	900 m/s	~ 500 kg
Perijove raise	40 m/s	~ 20 kg
Endgame	200 m/s	~ 100 kg
Europa Orbit Insertion	450 m/s	~ 200 kg
SubTotal	1590 m/s	~ 820 kg

In addition: ~ 200 kg for propulsion system
Total ≈ 1,000 kg necessary for propulsion

* From Europa 2012 Study Report (Unlimited Release)

- MAGNETOUR

Tether mass assuming aluminum, d = 10 cm, t = 0.05 mm



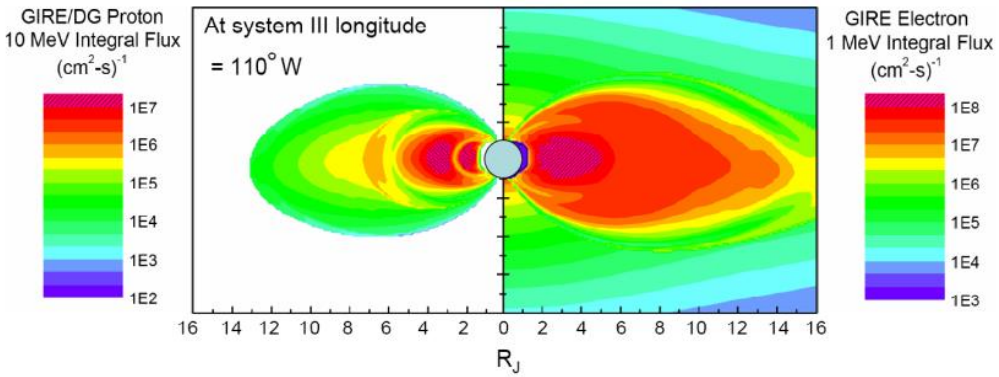
Tether mass likely between 100 and 200 kg

→ At least **800 kg** savings expected

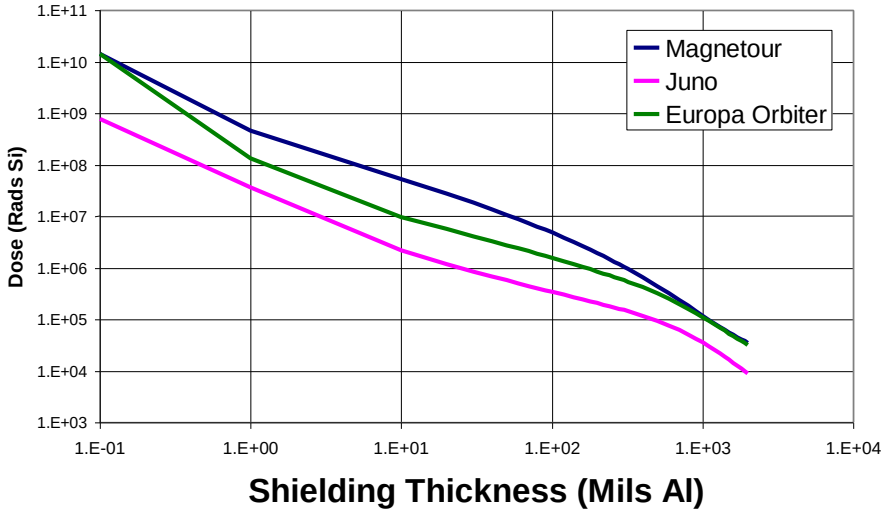
Pre-decisional: for information and discussion purposes only

Radiation

- Radiation GIRE Model
- InterMoon Superhighway trajectory tested



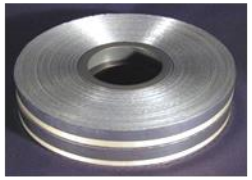
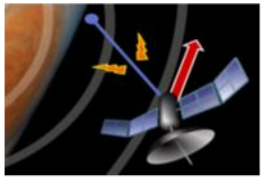
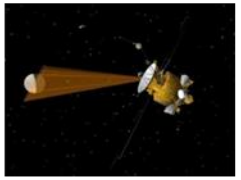
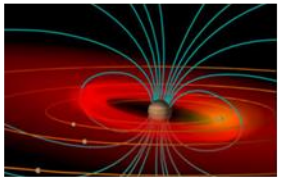
- For > 700 Mils Al, radiation doses of Europa orbiter and Magnetour are equivalent !



Total Dose Versus Shielding Thickness for Three Jupiter Missions

Pre-decisional: for information and discussion purposes only

Technology Roadmap

	Mission Design	Tether Design	Tether Functionality	Science Instruments	Environment Protection
					
Technologies	• InterMoon superhighway • Lunar weakly captured orbits • Coupled magnetic and gravity dynamics • Robustness to uncertainties • Tether dynamics & control	• Materials • Length • Deployment • Wire or tape tether ?	• Electrodynamic propulsion & power • Electrostatic propulsion & power • Hollow cathode thruster • UHF antenna • Radiation shield • Magnetic sensor	• Remote sensing from L1, L2 points • Low-power electronics	• Radiation • Micrometeroids • Electric discharge • Temperature ranges • Local and temporal variations

Pre-decisional: for information and discussion purposes only

Conclusion

- Yes, it seems a viable concept (at Jupiter at least)
- Tether length of at least 25 km
  - Enough for capture and small maneuvers between moons
- Promising quasi-ballistic, feasible tour solution at Jupiter
  - Significant mass savings
  - Reasonable radiation dose

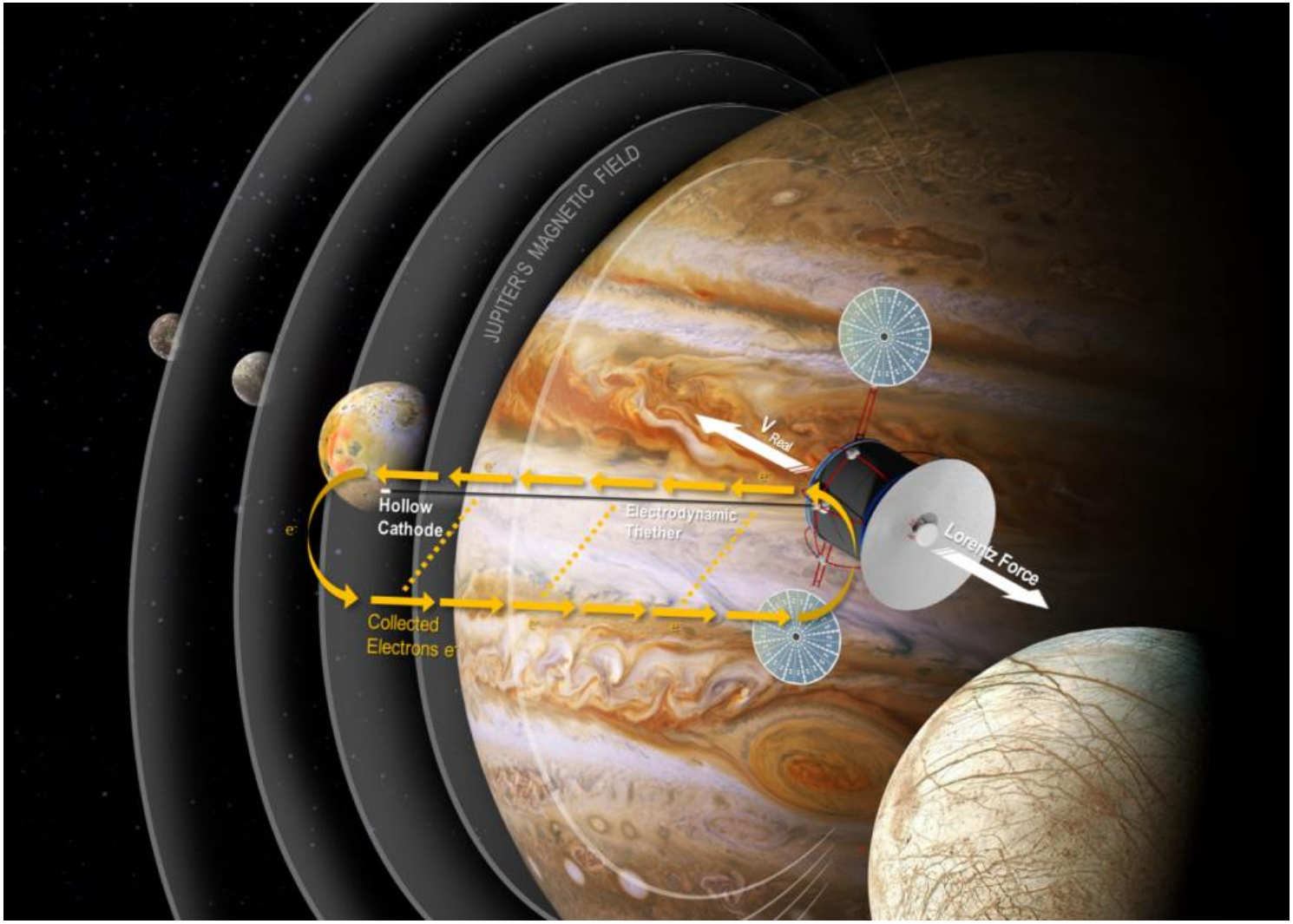
- New paradigm in exploration of planetary systems
  - ‘Free-lunch’ tour: no propellant nor power supply
  - Electrodynamic tether as an alternative to nuclear reactor (JIMO)

Pre-decisional: for information and discussion purposes only

Acknowledgements

- NASA Innovative Advanced Concepts (NIAC) program
- Maximilian Schadegg, Kevin Bokelmann, Damon Landau, Raul Polit-Casillas, Nathan Strange, and Daniel Grebow

Questions ?


JUPITER'S MAGNETIC FIELD
V_{Real}
Hollow
Cathode
Electrodynamic
Thether
Lorentz Force
Collected
Electrons