Lorentz-Actuated Orbits:

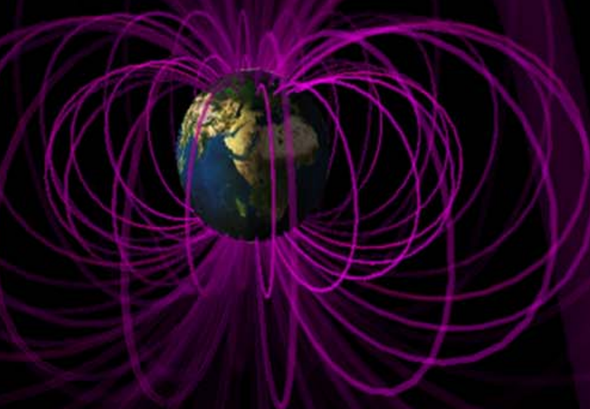
Electrodynamic Propulsion without a Tether

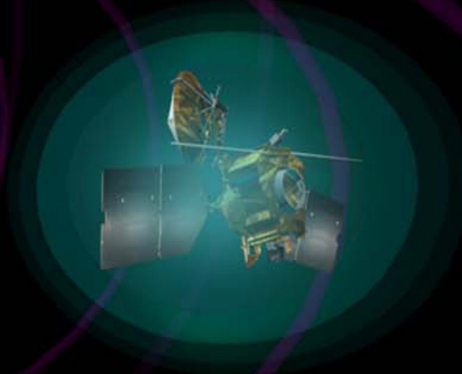
Dr. Mason A. Peck

Cornell University

Sibley School of Mechanical and Aerospace Engineering

Collaborators





Binghamton University
- James Brownridge

Cornell University
- Justin Atchison
- Patrick Conrad
- Joanna Hinks
- Parker Imrie
- Mike Kelley
- Marianna Kondratovich
- Joseph Shoer
- Brett Streetman

HANSCOM AFB
- David Cooke
- Adrian Wheelock
- Shu Lai

Northrop Grumman Space Technologies
- Bernard Morgowicz

Overview

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The Big Idea

- Lorentz-augmented celestial mechanics
- Electrodynamics in a rotating frame
- Fundamental design drivers

FAQ: Designing LAO-capable Spacecraft

- Capacitance
- Plasma interactions
- Power
- System architectures

Some Applications

- Earth escape & Jupiter capture
- Rendezvous and formations
- Surveillance
- Interstellar spacecraft

Experimental Program

The Idea: a Lorentz-Actuated Orbit (LAO)

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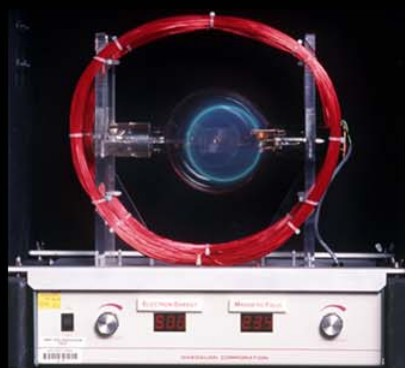
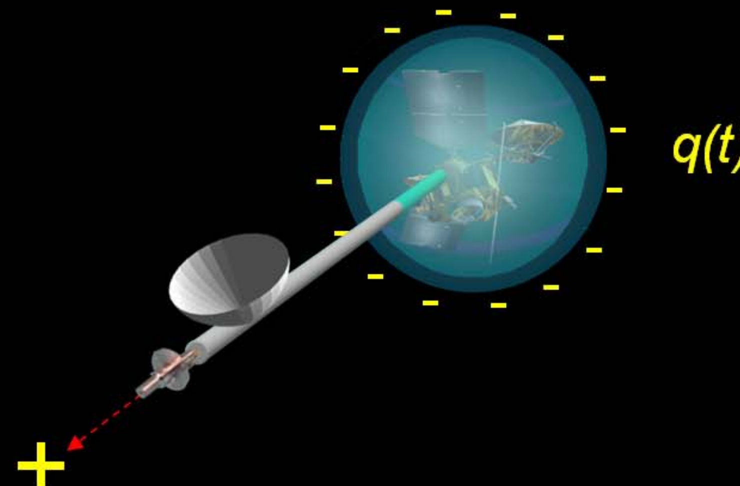
The Lorentz force accelerates charged particles traveling in a magnetic field. Can it be used to control the motion of a spacecraft?





- **For example, Burns, Schaeffer, et al.; Cassini, Voyager data**
  - Measurements show that Lorentz resonances determine structures in the rings of Jupiter and Saturn
  - Micron-size particles
  - A few volts of potential

The Idea: a Lorentz-Actuated Orbit (LAO)

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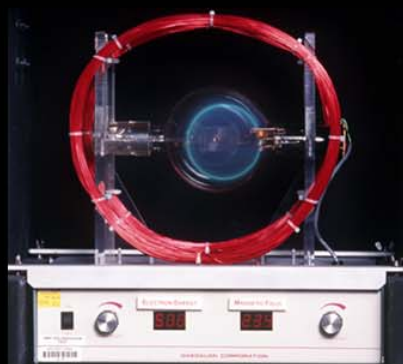
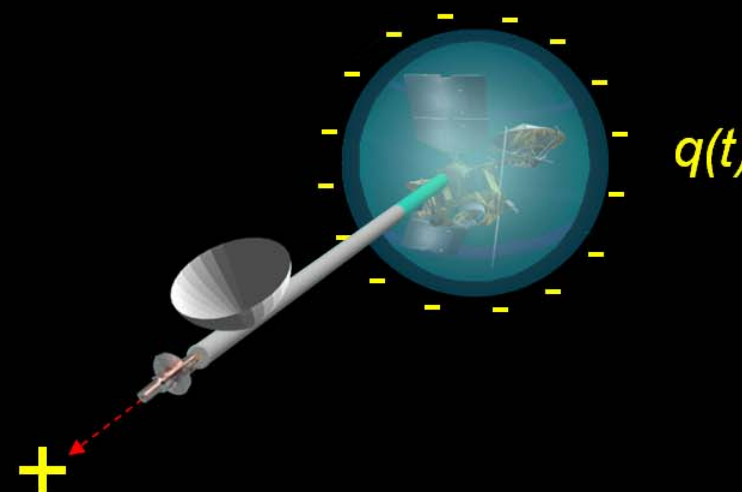
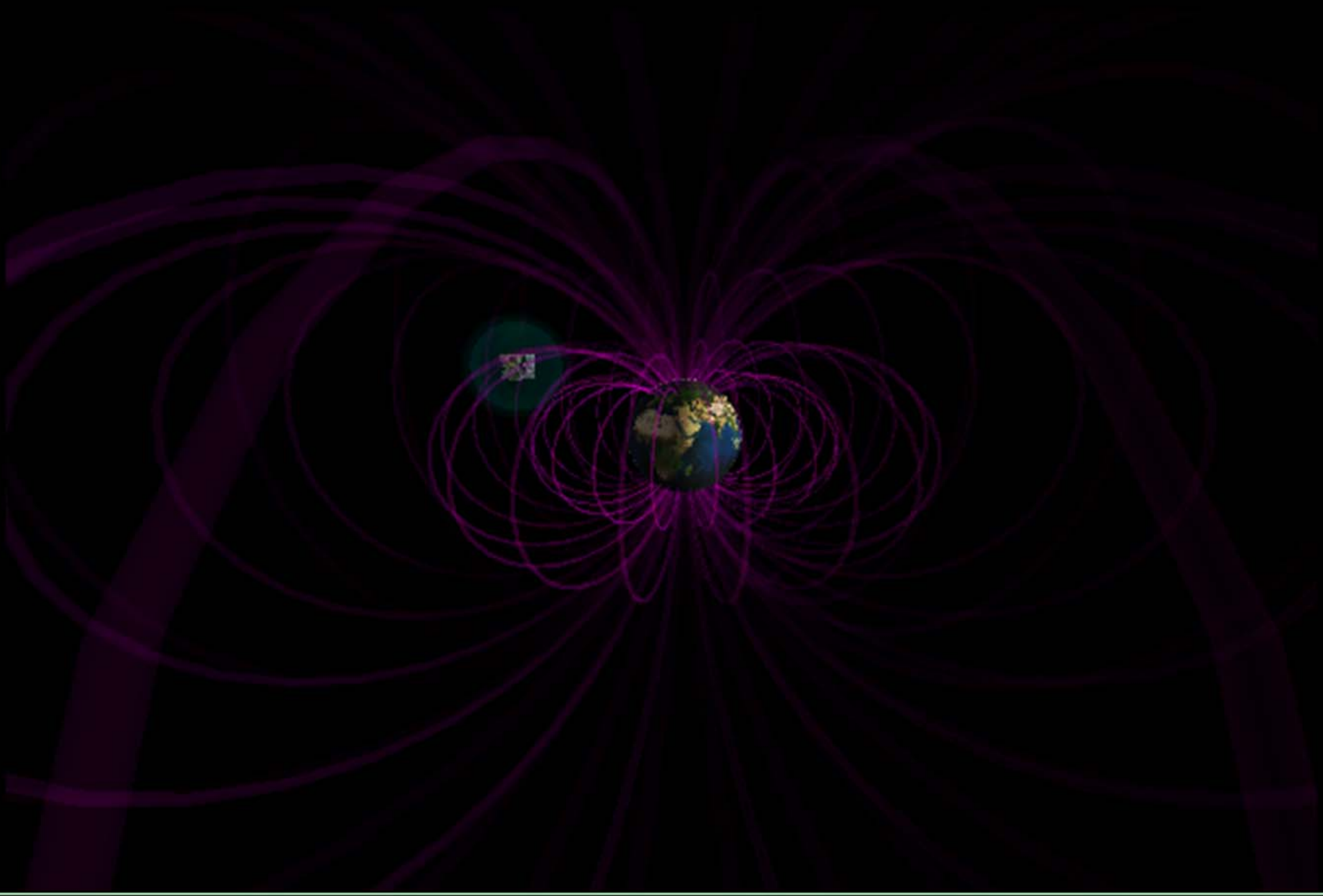
The Lorentz force accelerates charged particles traveling in a magnetic field. Can it be used to control the motion of a spacecraft?





- **It's not an electrodynamic tether**
  - Current in a tether interacts with the geomagnetic field: $\boldsymbol{J}\times\boldsymbol{B}$
  - Electrons traveling at cm/sec through a conductor
  - This spacecraft's charge *is* a current (high charge at high speed): $q\mathbf{v}\times\boldsymbol{B}$
  - ***LAO propulsion is attitude-independent; the spacecraft can be much more compact and is capable of higher-agility attitude motion***

Electrodynamics in a rotating frame



Electrodynamics in a rotating frame

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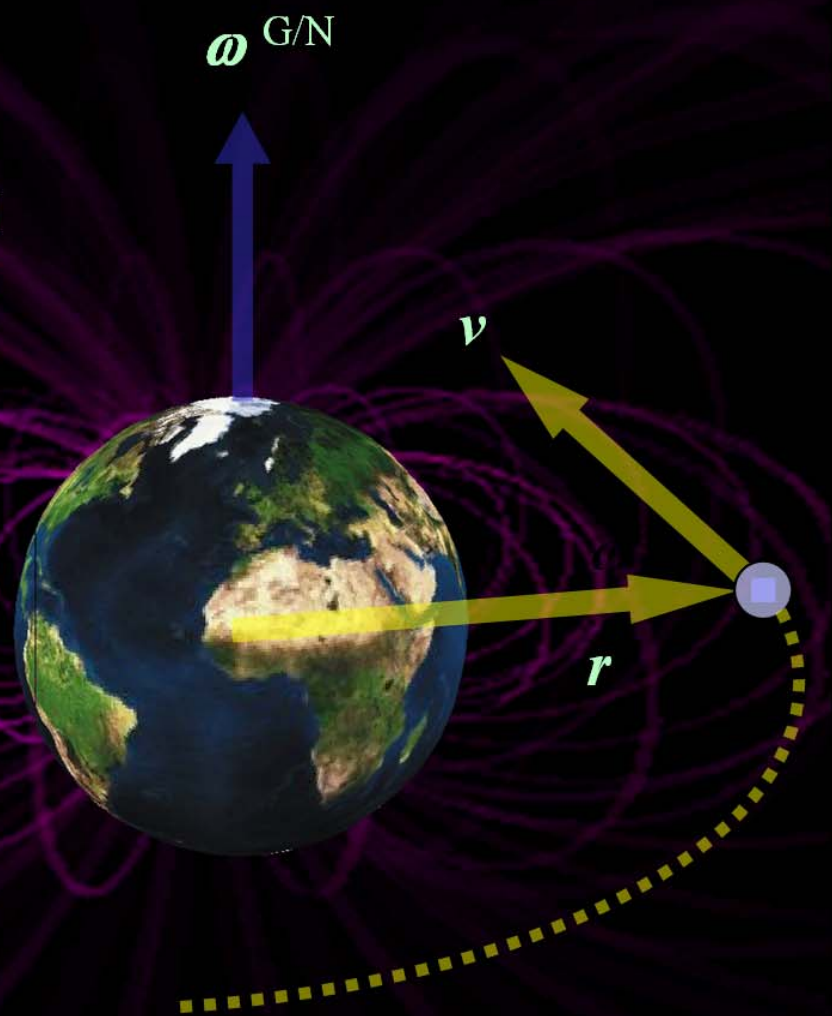
- Lorentz Force, as you've seen it before:

$$\boldsymbol{F} = q\boldsymbol{E} + q\boldsymbol{v} \times \boldsymbol{B}$$

- But *B* rotates with the planet
  - Rotating frame G; inertial frame N
  - Position $\boldsymbol{r}$ and angular velocity of G w.r.t. N $\boldsymbol{\omega}^{G/N}$
  - Classically, orbital velocity is inertial:

$$\boldsymbol{v} = \frac{{}^{N}d}{dt}\boldsymbol{r} = \frac{{}^{G}d}{dt}\boldsymbol{r} + \boldsymbol{\omega}^{G/N} \times \boldsymbol{r}$$

- This distinction matters because the rotating *B* acts as an electric field in N (the "co-rotational" field).



Fundamental Design Principles

$$a = \frac{q}{m} v \times B$$

Acceleration depends on charge-to-mass ratio *q*/*m*

Maximize *q*/*m*

- Maximize *q*
- Minimize *m*
  - High-density charge storage
  - Lightweight power (high "specific power" W/kg)

Fundamental Design Principles

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$$q = CV$$

Charge depends on self-capacitance and potential

- **Maximize capacitance**
  - Geometry of conductors
  - Space charge within insulators (e.g. electrets)
- **Maximize potential**
  - Emit charged particles with high energy
  - Electrons, positrons, ions, alpha particles…

Fundamental Design Principles

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$$P = IV$$

Power depends on rate of particle expulsion (beam current) and the particle potential (beam energy)

Ambient plasma discharges the spacecraft

- A continuous current is required to combat discharge
- Minimize current to minimize power
  - Current above the incident plasma currents does not help
  - Exploit natural processes (e.g. alpha decay) that requires no input power via solar array *et al.*

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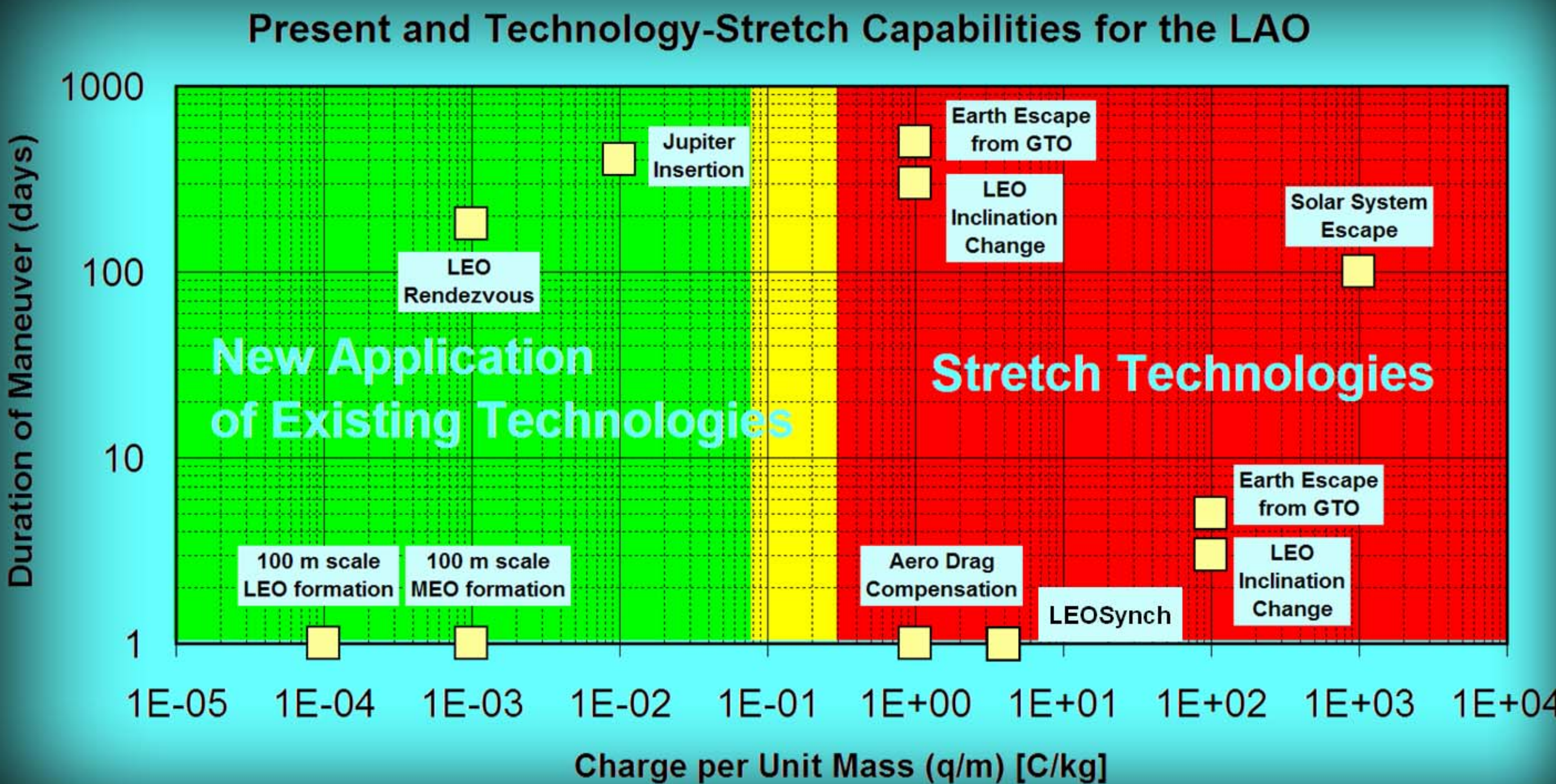
How much charge do you need?

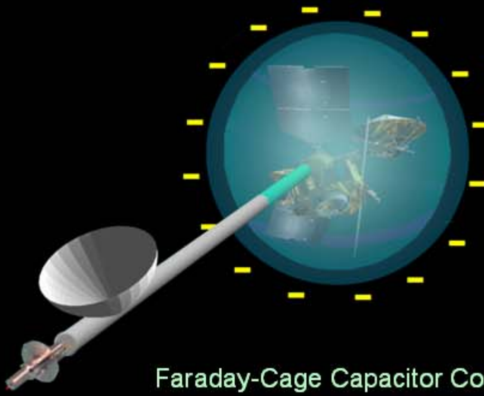


How is charge established and maintained?

- **Natural charging (due to plasma interactions and/or photoelectric effect) can't offer more than a few kV.**
- **Large SC require hundreds of kV if the capacitance is small**
  - Spherical shell is an example
  - Emit ions or electrons via a plasma contactor
  - Electron emission is a little easier and lighter, and it requires no propellant
- **Overcome discharge into the plasma**
  - Power required depends on altitude, area, space weather…

400 kV Van de Graaff Generator

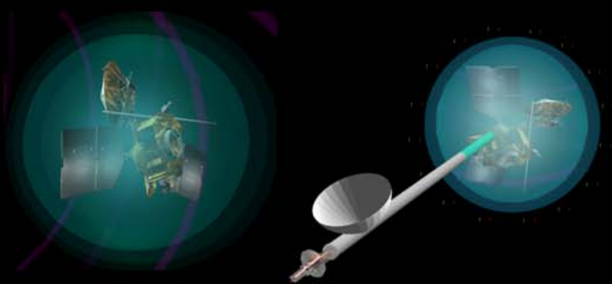
L'Garde Conductive Sphere



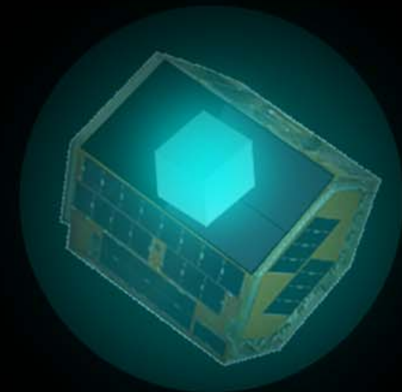
Faraday-Cage Capacitor Concept

Self-capacitance

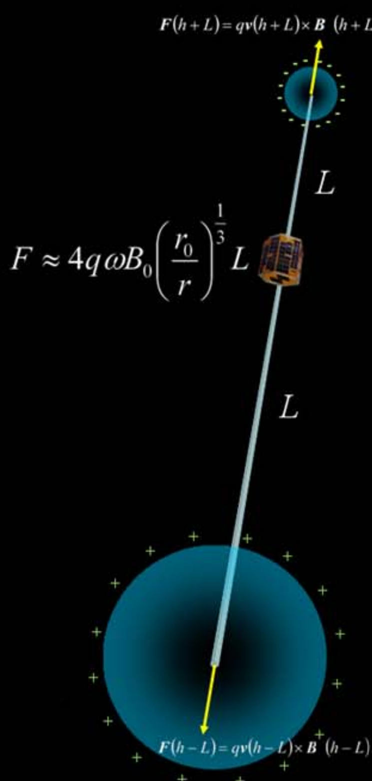
– The spacecraft body, or part of it, holds a net charge

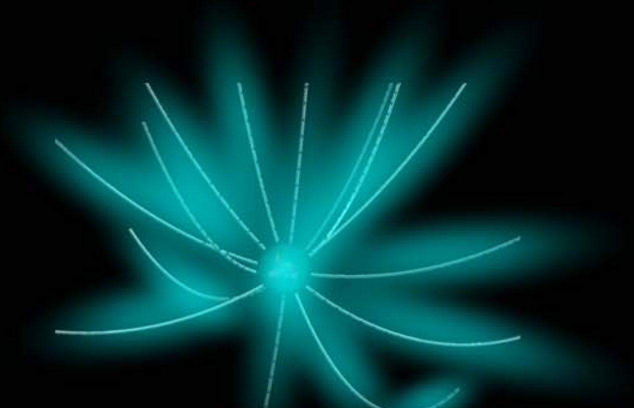


Conductive Spherical Shell



Volumetric Electret Capacitor





Multiple-Filament Capacitor

Single-Filament Capacitor

Differential LF

FAQ: Capacitance

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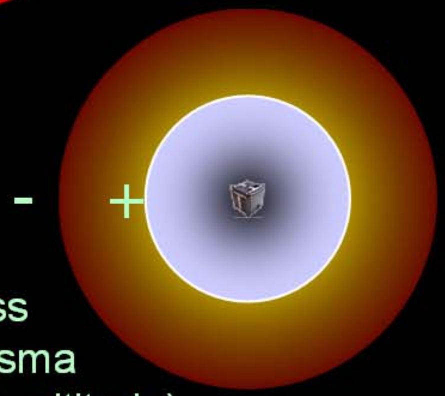
Plasma Interactions

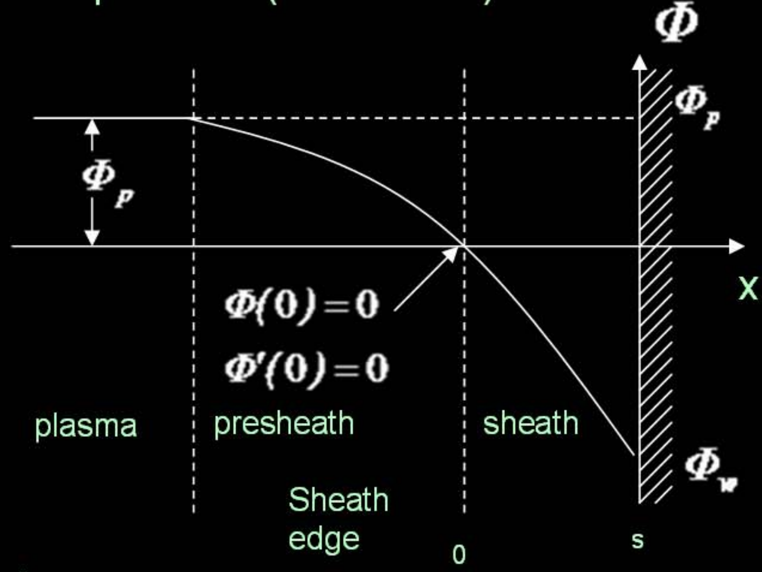
- The key sizing parameter is charge per unit mass (*q/m*), which is proportional to the acceleration (Δ*v*) available
- Charge depends on capacitance
- For a spherical spacecraft surrounded by plasma,

$$C \approx 4\pi\varepsilon_0 \frac{R\left(R+\lambda_{De}\right)}{\lambda_{De}}$$

- Where λ_{De} is the Debye length, ~the thickness of an oppositely charged sheath that surrounds the charged body.



Sheath thickness depends on plasma temperature (i.e. altitude)



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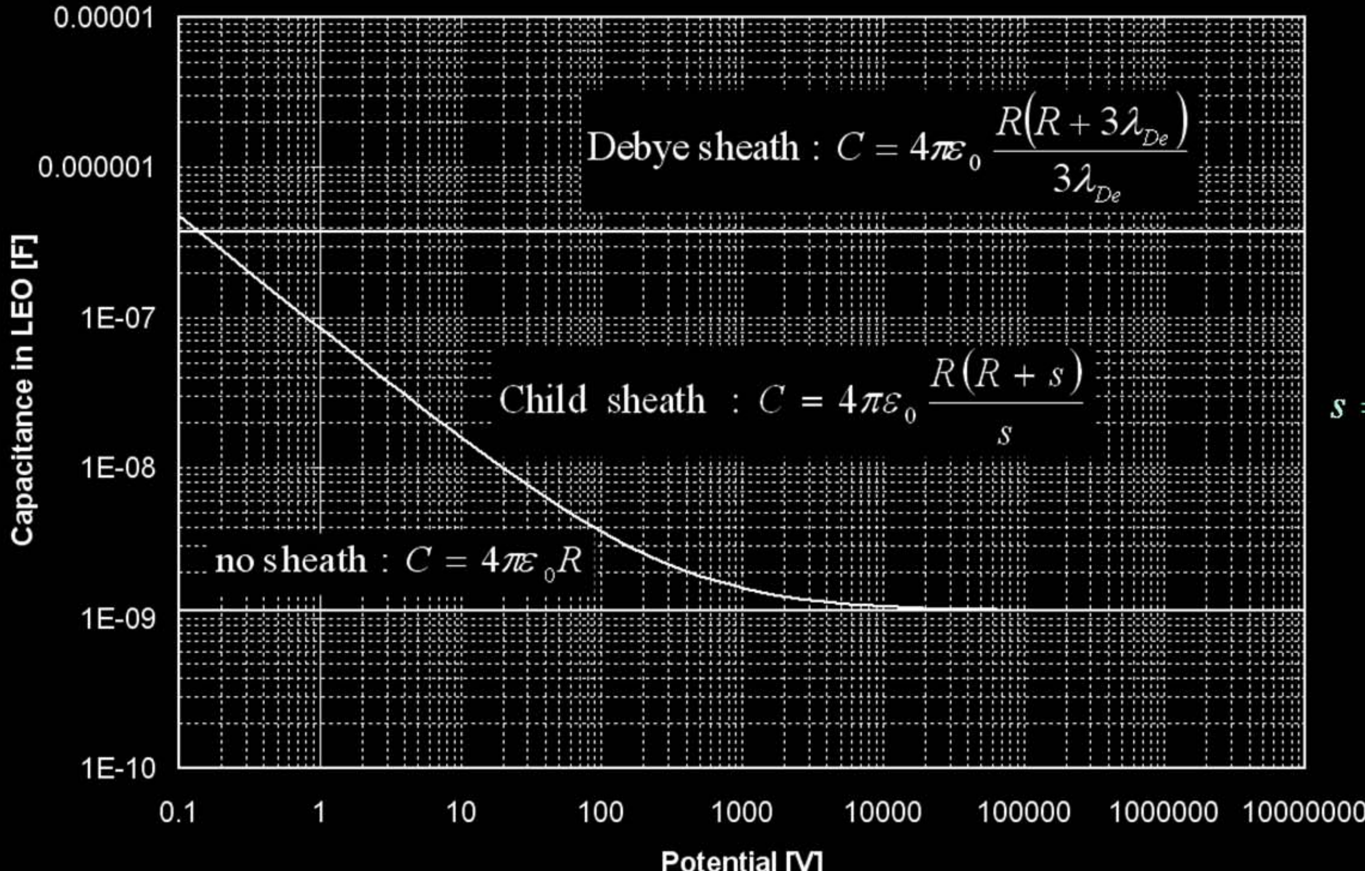
High-Voltage Sheath Requires Careful Modeling



$$s = \frac{\sqrt{2}}{3}\lambda_{De}\left(\frac{2V_0}{T_e}\right)^{\frac{2}{5}}$$

Comparison of 10m Spherical Capacitance in 1200K LEO Plasma for three Sheath Thickness Models

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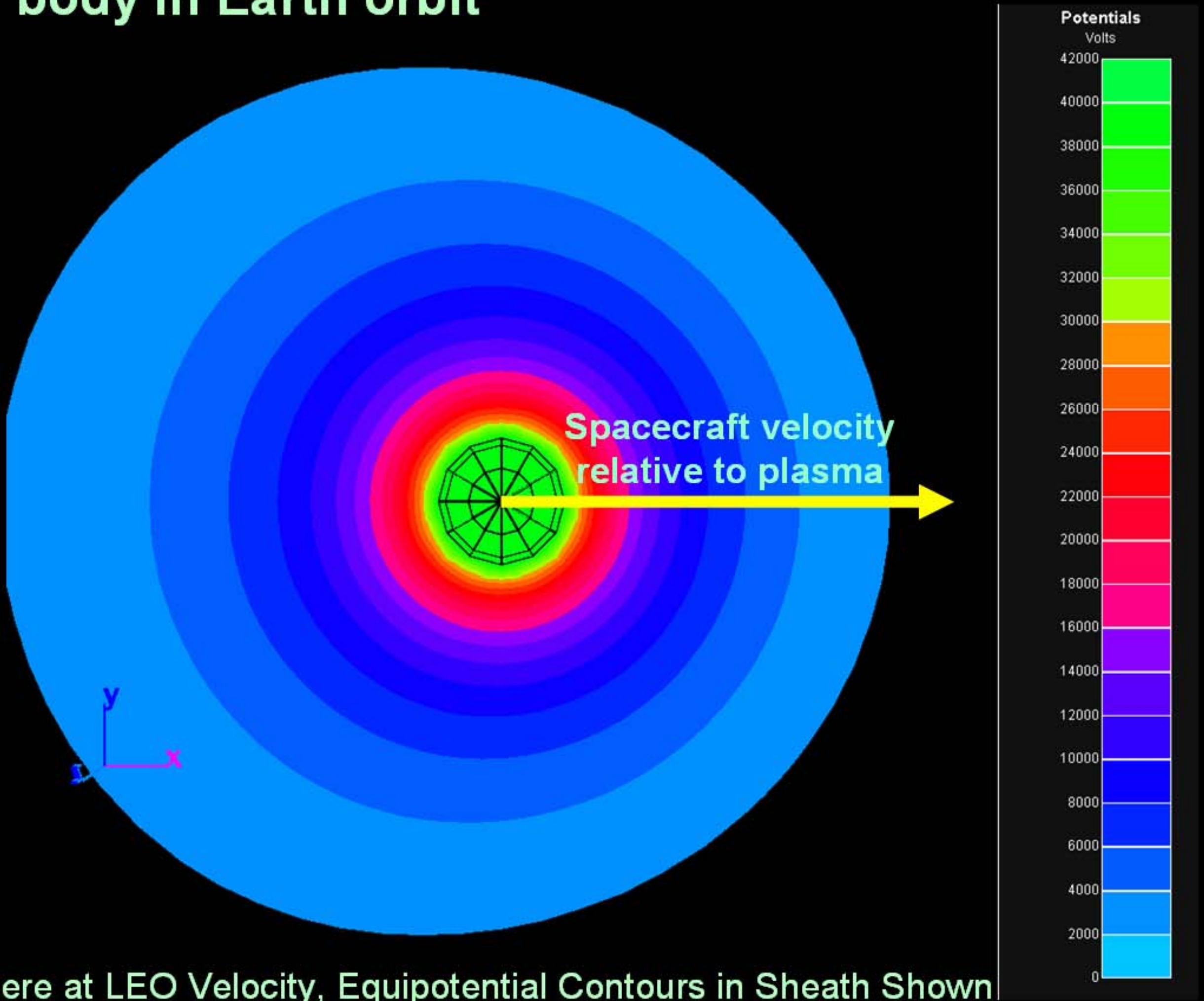
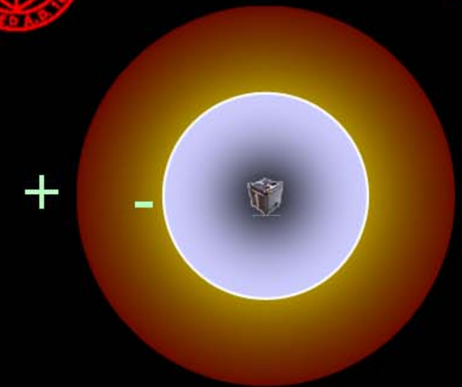
We have adapted NASA's NASCAP software to calculate the total charge on a body in Earth orbit



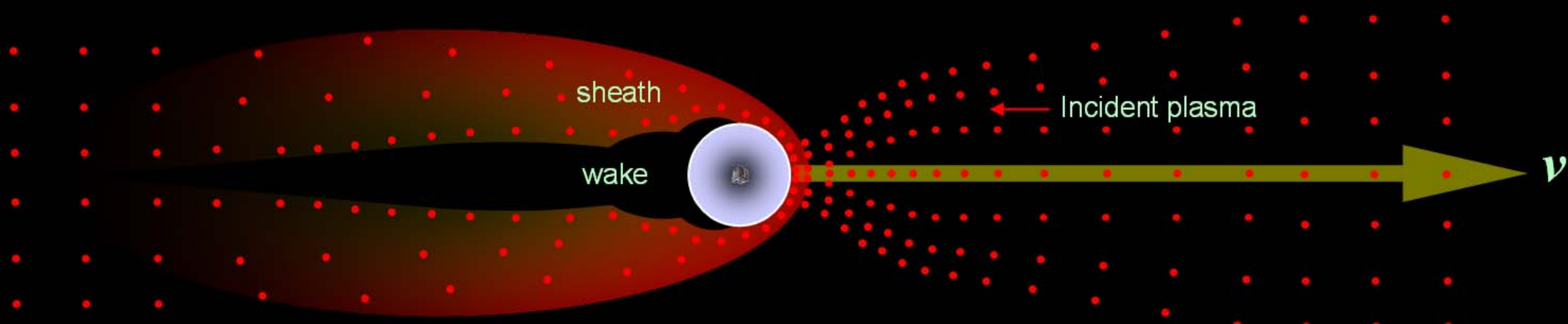
1m, 42kV Charged Sphere at LEO Velocity, Equipotential Contours in Sheath Shown

Doesn't the Debye Sheath Cancel the Lorentz Force?

- NO
  - The charge in the sheath is equal in magnitude and opposite in polarity.
  - Forces on the sheath are transmitted to the spacecraft via Coulomb interaction.
  - But particles in the sheath do not travel with the spacecraft.
  - So, the sheath does not feel the Lorentz force.



$$C \approx 4\pi\varepsilon_0 \frac{R\left(R+\lambda_{De}\right)}{\lambda_{De}}$$



Particles' velocity is more-or-less fixed in the plasma, which travels with the geomagnetic field

FAQ: Power

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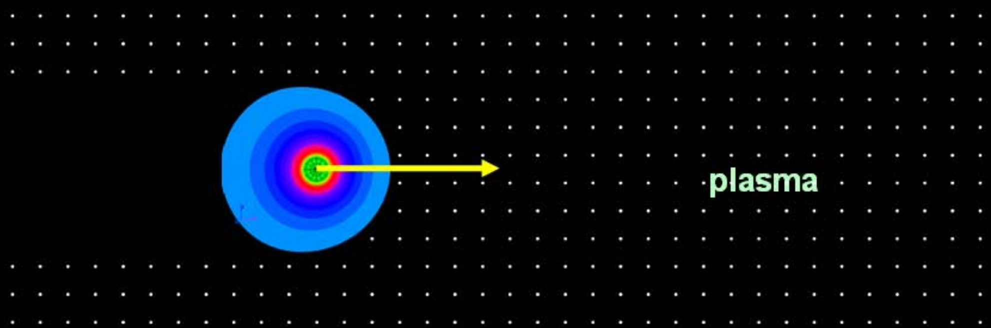
Power-Plasma Interactions

- **Ram current from plasma determines power requirement**
- **Cross-sectional area of spacecraft+sheath**
  - Constitutes a kind of Coulomb drag (not significant)
  - Encounters charged particles that spiral inward toward the spacecraft (significant)
  - High potential -> high ram currents
- **Spacecraft can charge to a potential equal to the beam energy**
  - Power is required to expel charge at a rate that at least matches the ram current, at the spacecraft surface potential (P=IV)



- **FYI**
  - Polar LEO electron current: negative $6\times10^{-6} - 6\times10^{-5}$ A/m^2
  - Polar LEO ion current: positive $4\times10^{-8} - 4\times10^{-7}$ A/m^2

FAQ: Power

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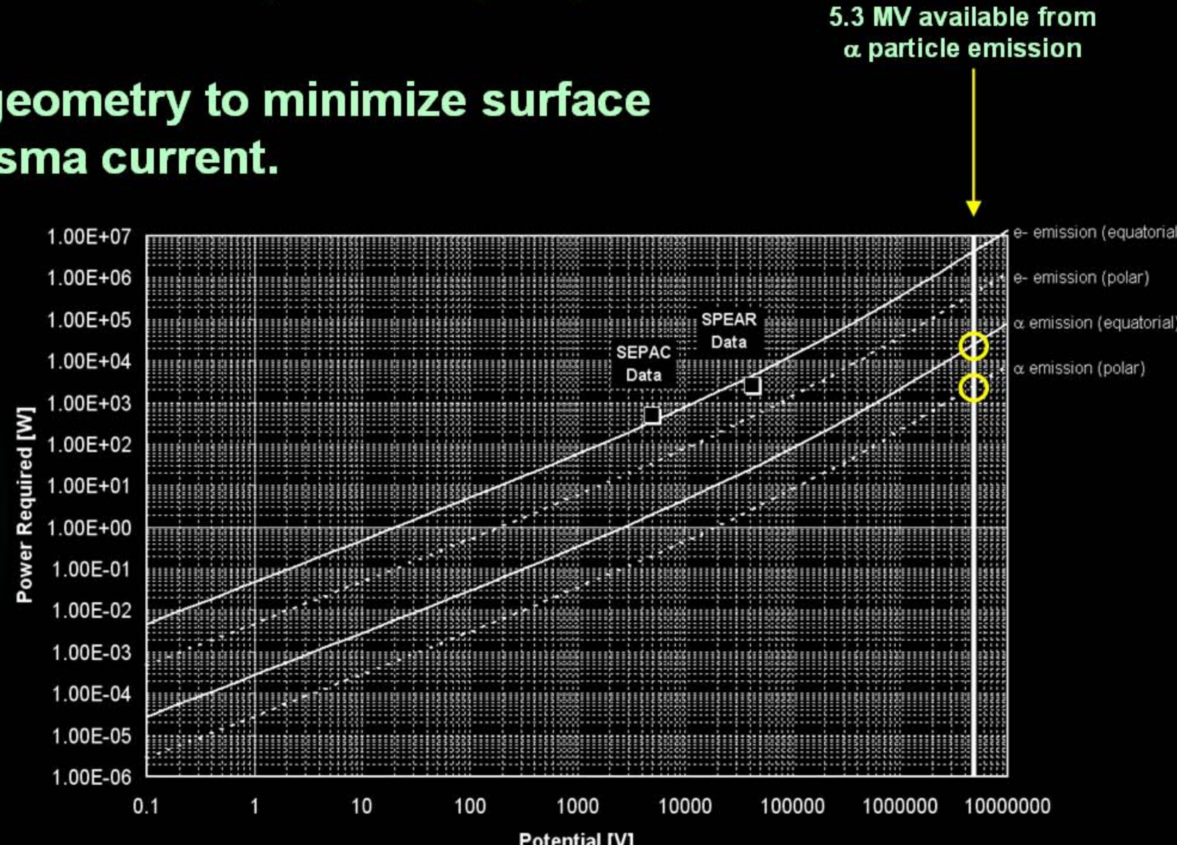
Preferred Solution

- Charge negative to repel electrons.
- Emit α or β^- particles via an isotope undergoing natural decay.
- Maintain a compact geometry to minimize surface area that collects plasma current.

5 kW – 50 kW

Available from 0.1 - 1 kg of ^{210}Po for 1 year



Power required to maintain a meter-scale spacecraft at high potential

FAQ: Power

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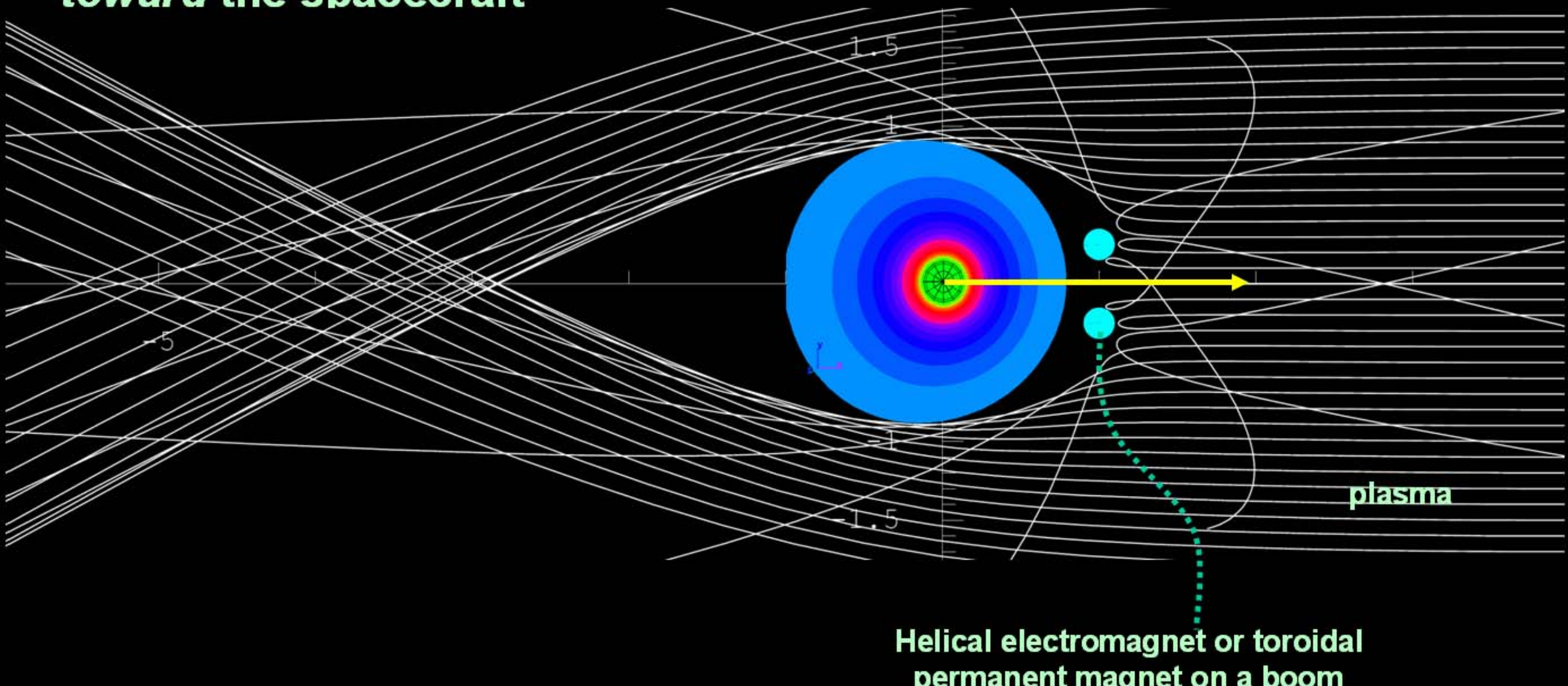
For much higher *q/m* or lower power or no ^{210}Po…

- Sweeper magnet
- Deflect incident ions before they adhere to the spacecraft's surface
- Reduce power to 1%-10% of current predictions
- Even higher performance is possible if electrons can be deflected *toward* the spacecraft



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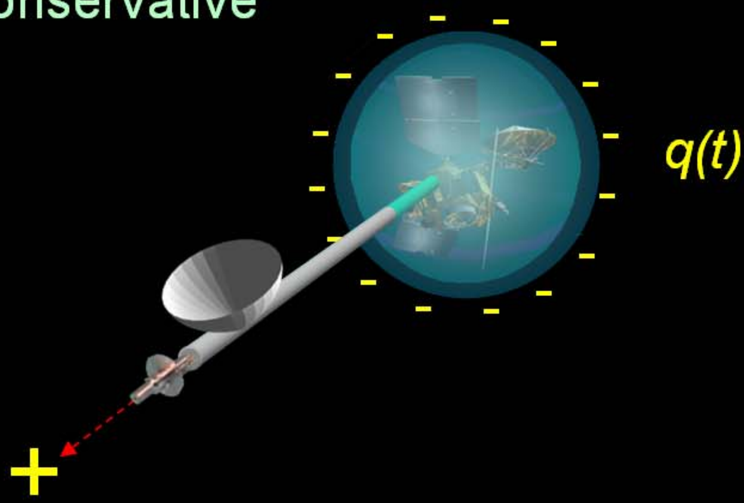
Attempt to bound worst-case design metrics

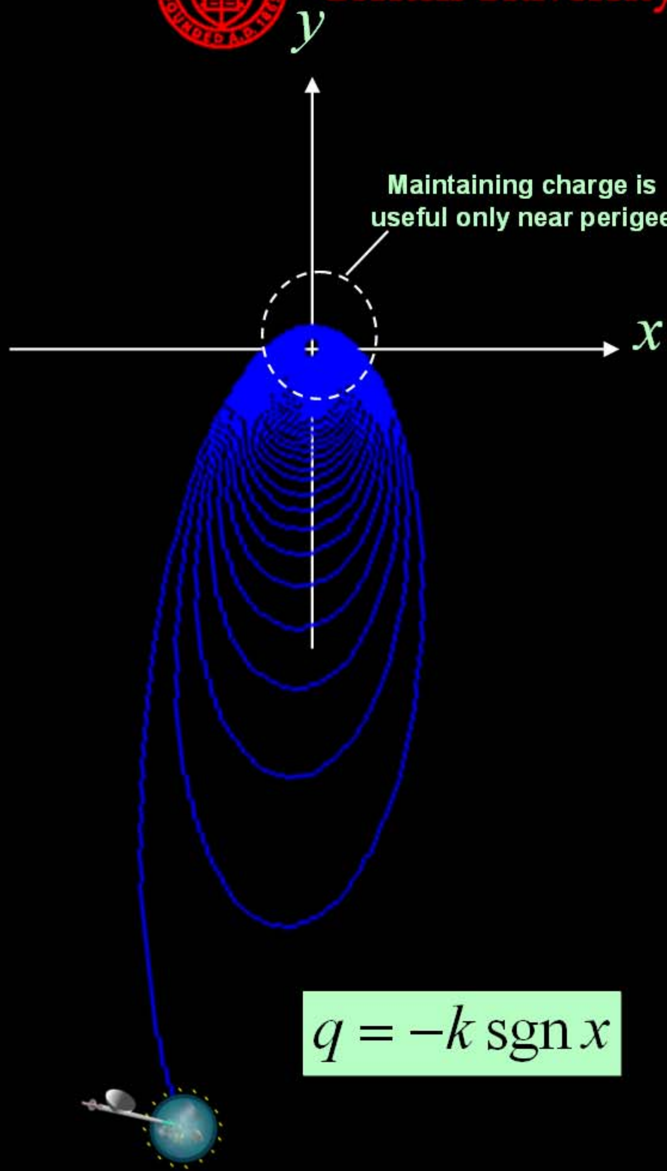
- Evaluate feasibility
  - Helps identify required technology advancements
- Use spherical shell as a low-risk, high TRL technology
  - Represents least efficient charge-storage method
- Consider ion beam power and sphere radius as metrics
- Use worst-case charging power (Shuttle SEPAC results)
  - Probably 10x conservative



Some Applications

Earth Escape

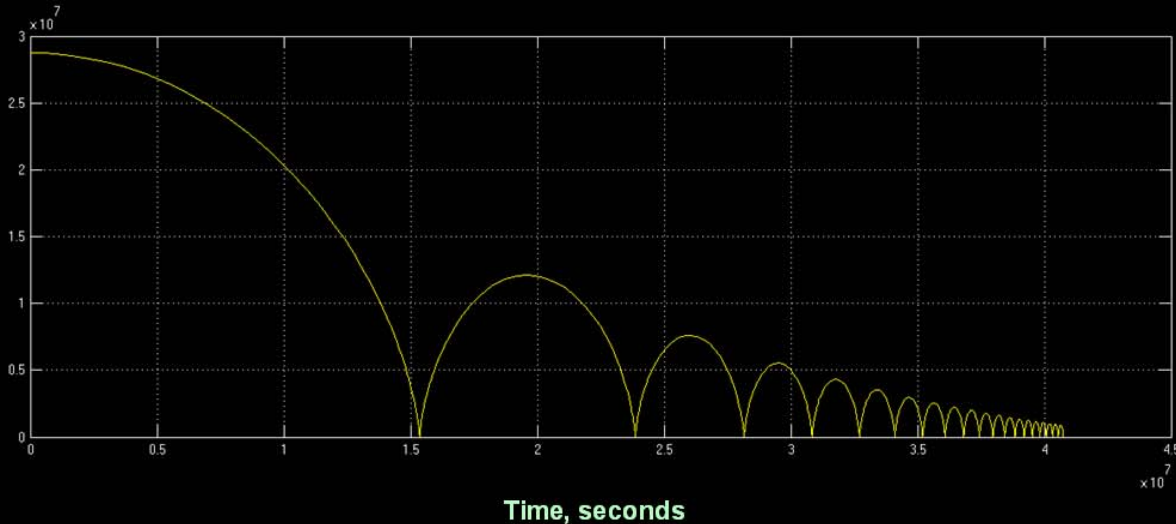
- It takes about 1 year for a q/m=5 C/kg spacecraft to escape earth orbit, with appropriate phasing of charge with true anomaly.
- This level of charge represents high risk for the spherical-shell architecture because the plasma behavior is unknown, but its prospect inspires other technical solutions like electrets.
- Specs for a sphere:
  - 100 kg spacecraft
  - 5 MV potential
  - r=50 m sphere



$$q = -k \operatorname{sgn} x$$

Jupiter Capture

- Jupiter's magnetic field is about 20,000 times more powerful than Earth's.
- Its faster rotation (once every 9 hours) means that the co-rotational field can contribute energy to an LAO quickly.
- For *q/m*=0.01 C/kg, a spacecraft can transition from a parabolic orbit at Jupiter to the orbit of Ganymede in a little over a year.



Altitude above Jupiter (R_j=71,492 km) during 472 Day Orbit Insertion

- Specs for a sphere:
  - 1000 kg spacecraft
  - 440 kV potential
  - r=15 m sphere

Some Applications

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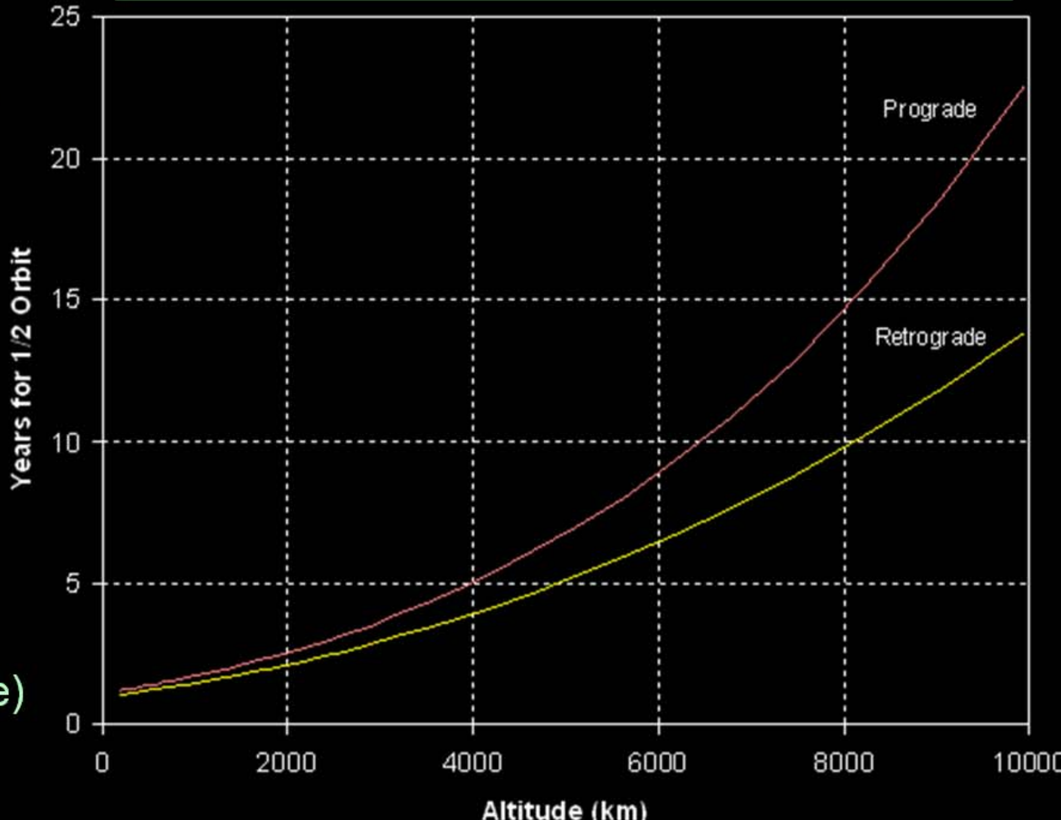
Rendezvous

- The potential function for an LAO alters Kepler's equation.
- Charge one spacecraft, or each of a pair, and one will catch up to the other ***at the same altitude***.
- Retrograde orbits catch up faster because the velocity in G is greater.

$$\omega = -\frac{q}{m}B_0\frac{r_0^3}{r^3} \pm \frac{\sqrt{\left(\frac{q}{m}B_0 r_0^3\right)^2 + 4r^3\left(\mu + \frac{q}{m}\omega_e B_0 r_0^3\right)}}{2r^3}$$



Time to Rendezvous (years) in Circular Orbit; q/m=0.001 C/kg

- Specs for a sphere:
  - 1 year rendezvous (worst case)
  - 10 kg spacecraft
  - 62 kV potential (6.2 kW)
  - r=4 m sphere

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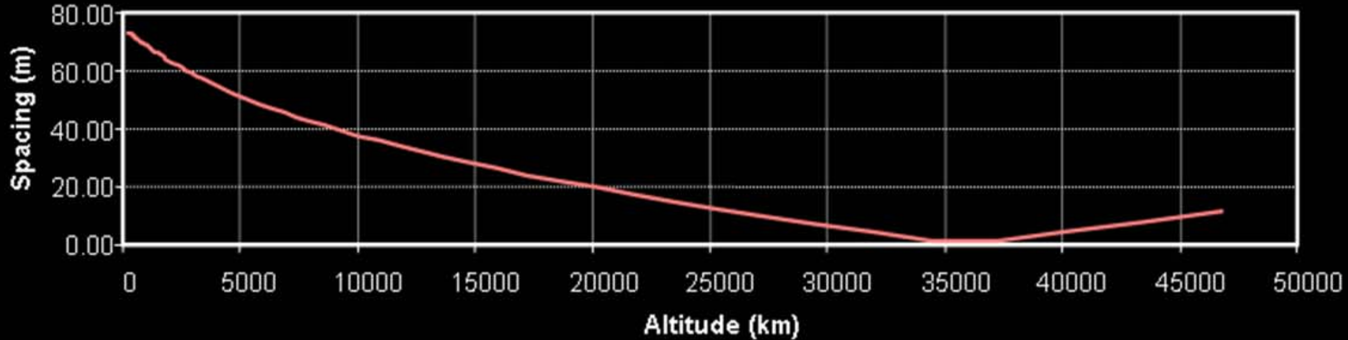
LAO Formations

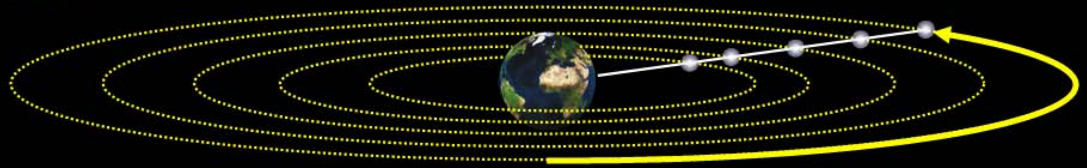
$$r = \sqrt[3]{\frac{1}{\omega^2}\left(\mu - \frac{q}{m}(\omega - \omega_e)B_0 r_0^3\right)}$$

- LAO spacecraft in a formation do not interact through Coulomb forces
- Spacecraft with different electrical potentials and orbital altitudes can orbit with the same period.
- New formations (3D paraboloid sparse-aperture telescope?)



Vertical Spacing for Circular Prograde Orbits: q/m=0.001 C/kg

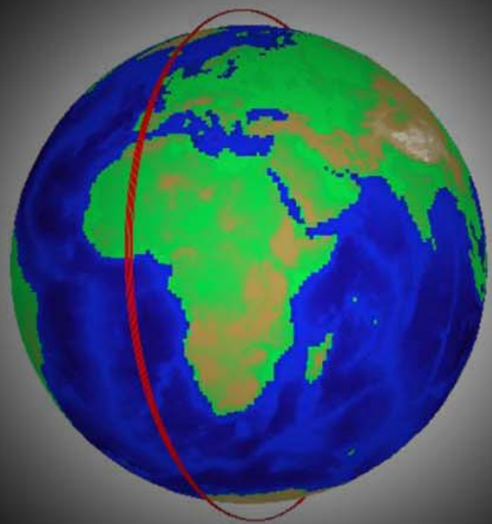
- Specs for a sphere:
  - 10 m vertical separation in LEO
  - 10 kg spacecraft
  - 10 kV potential (1 kW)
  - r=3 m sphere



Surveillance Application: LEOSynch

- Geosynchronous LEO spacecraft.
- Persistent coverage of a single longitude.
- Re-task a satellite to reach any longitude on Earth within 6 hours.

$$\left(\frac{q}{m}\right)_{GT-1} = \frac{\omega_E r^3}{B_0}$$



- Specs for a sphere:
  - 100 kg spacecraft
  - 5 MV potential (5-50 kW)
  - r=75 m sphere *or* ~10 km of filaments *or* ~10 kg thin-film electret material

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Surveillance Application: LEOSynch

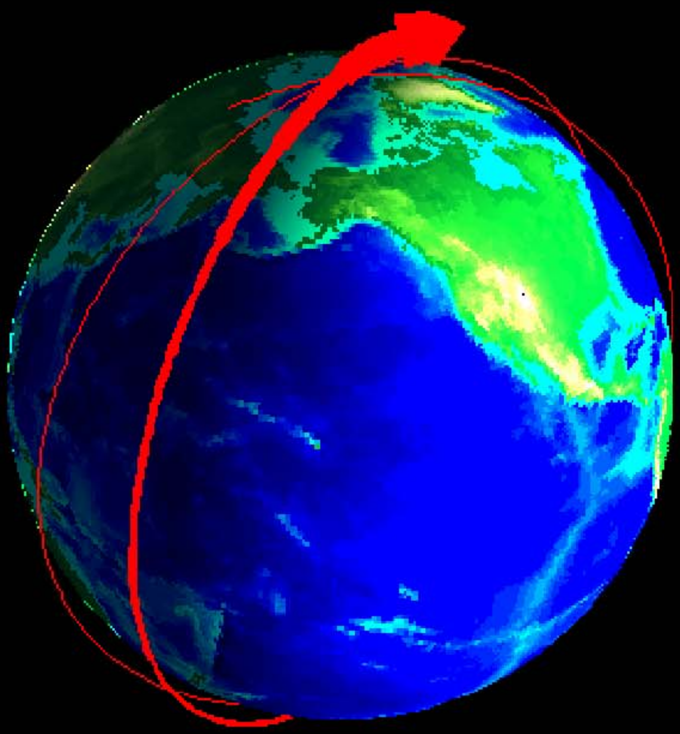
- In general, quickly pre-cessing polar orbits

$$\frac{q}{m} = \frac{\dot{\Omega}_{avg} r^3}{B_0}$$

- Cancel J_2
- Sun synchronous at many altitudes and inclinations
- Geosynchronous at LEO altitude!

$$\left(\frac{q}{m}\right)_{GT-1} = \frac{\omega_E r^3}{B_0}$$

$$F = qv \times B$$



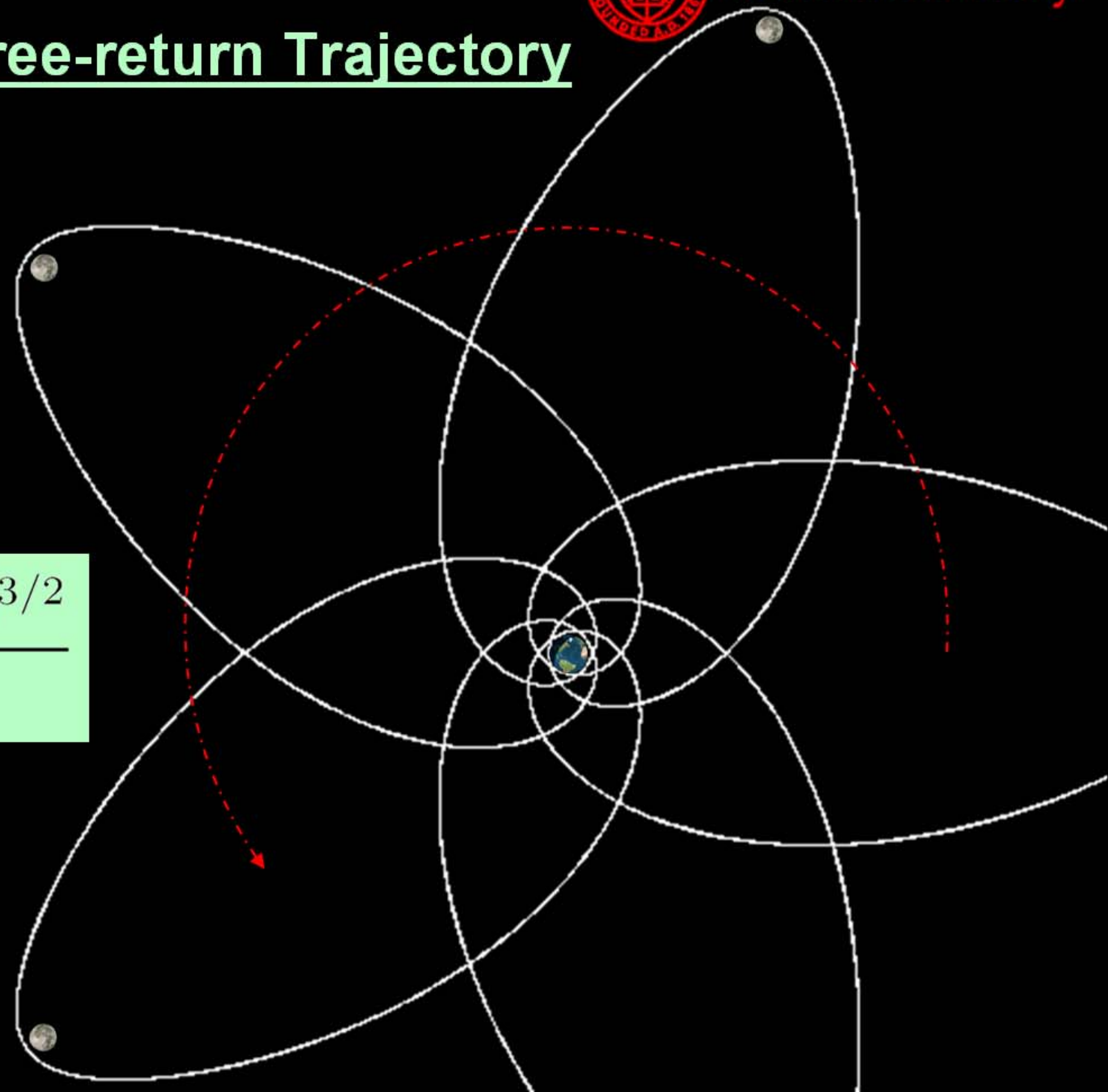
Continuous Lunar Free-return Trajectory

- Earth-moon-earth once per orbit
- Apollo-era solution for astronaut safety (cf. Apollo 13)
- Lunar resupply and/or science

$$\frac{q}{m} = \frac{\dot{\omega}_{des} a^3 (1 - e^2)^{3/2}}{2B_0}$$

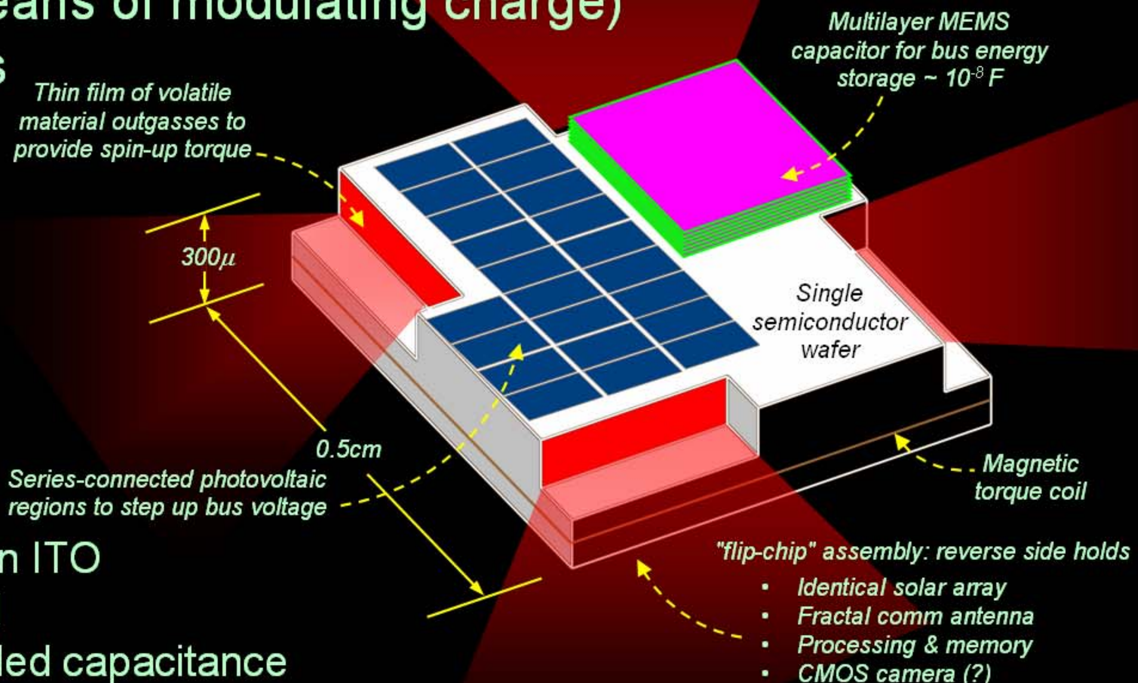
~55 C/kg

- Specs:
  - 10,000 kg spacecraft
  - 340 MV potential (!)
  - r=400 m sphere



Very Small Interstellar Spacecraft

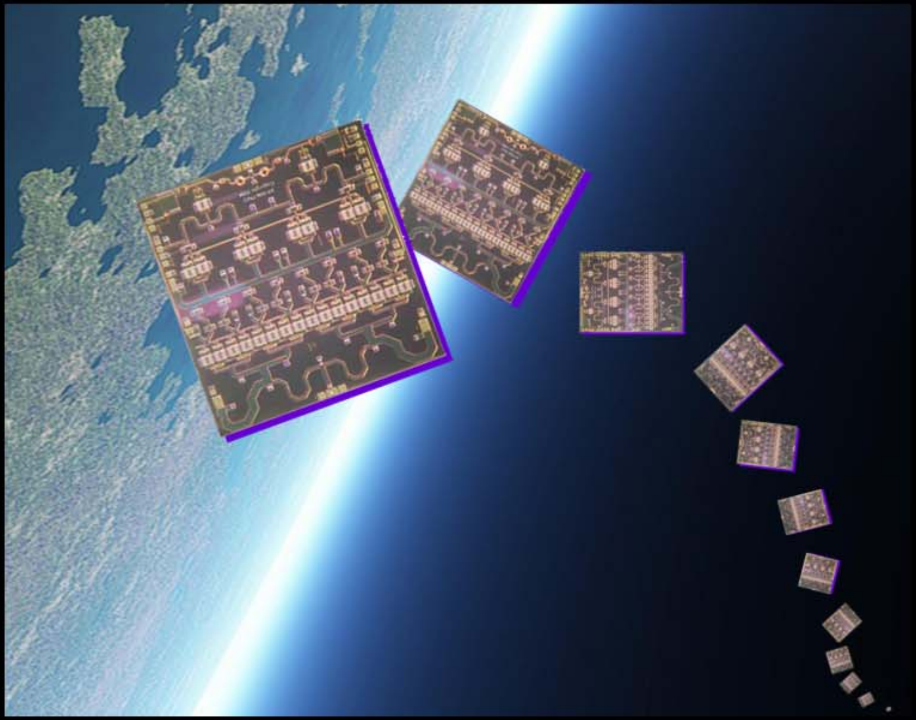
- Spacecraft on a chip: "SpaceChip"
- Orbit dynamics approaches that of charged dust grains
- Earth escape at plasma floating potential (no power!)
- Planetary-scale cyclotron
  - Ricochet between Earth and Jupiter in a series of LAO flybys (requires a means of modulating charge)
  - Bursty transmissions
  - *v* > 0.01c?



- Specs:
  - 10 mg spacecraft potted in ITO
  - 2V-20kV *floating* potential
  - Optional filaments for added capacitance

Very Small Interstellar Spacecraft

- **Mission architectures**
  - Billions relay data from distant locations
    - **Very low bandwidth**
    - **Need to continually populate pipeline**
  - A single chip encodes or transports a sample of human genome



Important Phase I Conclusions

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– **NIAC Phase I study shows that an LAO is even more feasible than we originally thought**
  - Formations & rendezvous are near-term possibilities
  - Others require higher capacitance per mass
  - A technology path may exist for extraordinary far-term applications

– **The plasma environment can be managed**
  - The plasma sheath helps by slightly increasing capacitance and lowering (or eliminating) electrostatic pressure
  - The plasma sheath does not cancel the Lorentz force
  - Relevant applications can be achieved in the near term (sphere specs bound power & size at the high end)

Future Directions

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– **Scaled tests of capacitor geometries**
  - The spherical conductive shell concept solves many problems, including ESD.
  - Electret tests continue
  - Filament curvature vs. capacitance
  - Hairy spheres

– **Perform plasma simulation and scaled testing**
  - Detailed evaluation of phenomena at high potentials, including effects such as surface imperfections.
  - SUNY Binghamton tests
  - HANSCOM AFB tests
  - SpaceChip demo

Lorentz-Actuated Orbits:

Electrodynamic Propulsion without a Tether

Backup Materials

FAQ: Power

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Preferred Solution

- Ion or e-beam emission powered by traditional sources requires very high specific power (W/kg), like ion propulsion.
- Acceptable specific power is available from natural emission of α or β particles by radioisotopes (NOT an RTG application or nuclear fusion).
  - ^{210}Po, formed by neutron bombardment of Bi, emits 5.3MeV particles.
  - $100/g, commercially available and used in deionizers
  - 138 day half life; becomes lead (stable)
  - 90 kW/kg after 1 year
  - Thin film on the surface of a sphere or filaments
  - Thermal implications only when the film is >thickness of paper
  - Other materials are under consideration.
- This high specific power is available only because of the unique application.
- This solution provides q/m>1.0, enabling many exciting applications.

What is the impact on other subsystems?

- **Structural and Mechanical Requirements for the Sphere Concept:**
  - Conductive
    - Acts as a Faraday cage, shielding components from differential charging
  - Transparent for solar power (unless nuclear power is possible)
  - Deployable (note that the charge inflates it)
  - Electret may be a MUCH better solution
- **Payload Options**
  - Has to work through a conductive shell
  - Maybe off until the spacecraft is in its operational orbit
- **T&C Options**
  - Lasercomm through the sphere
  - Antenna protrudes through sphere (ESD issues)
- **Attitude Control**
  - Little direct impact (the Lorentz force is independent of attitude)
  - Differential charge acts like a gravity-gradient effect, offering a means of attitude control (that's another project…)

FAQ: Capacitance

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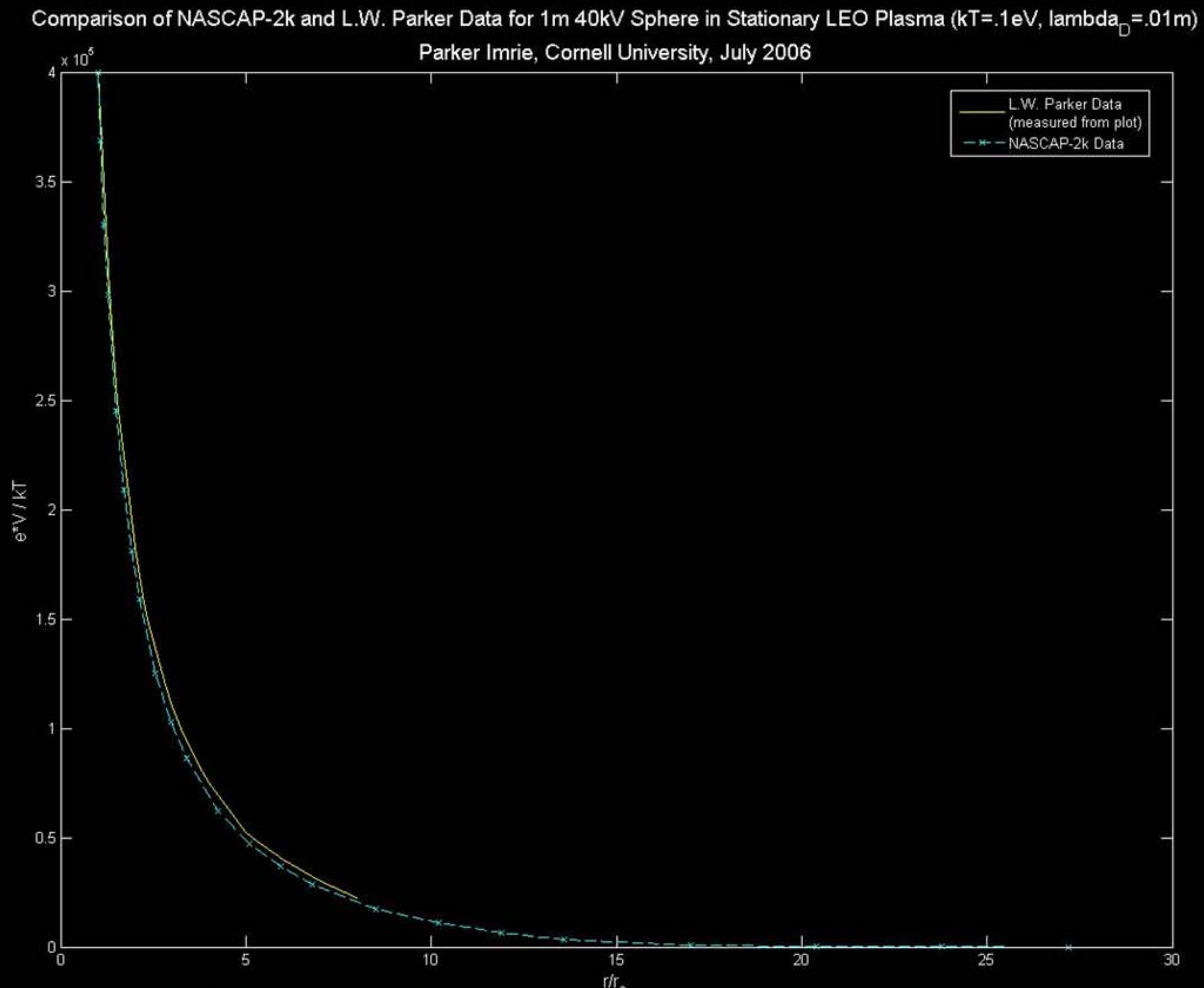
NASCAP analysis agrees with theory



Potential vs. radial distance from a 1m 40 kV sphere

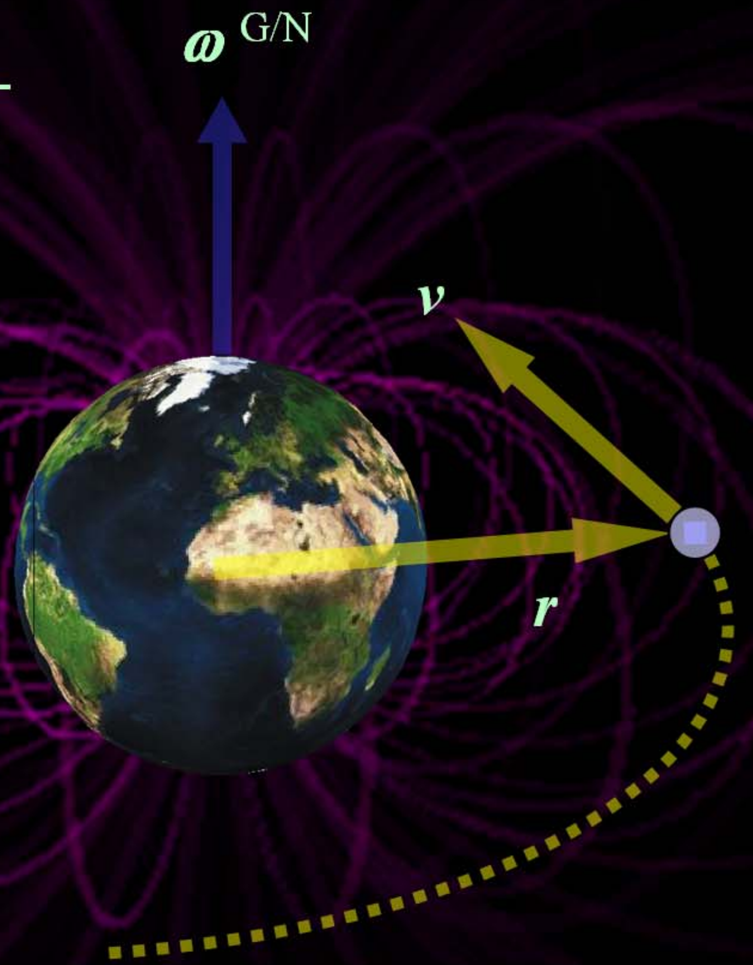
Electrodynamics in a rotating frame

- **We're interested in the case of *E*=0**
  - Debye shielding masks ***E*** from neighboring bodies (e.g. spacecraft)-- more later.
  - Time-varying ***B*** (due to solar wind) represents an ***E*** which may matter and we will address in future work

- **The Lorentz force becomes**

$$\boldsymbol{F} = q \frac{{}^{G}d}{dt}\boldsymbol{r} \times \boldsymbol{B}$$

because the co-rotational field in the rotating frame is zero



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An LAO's energy is not constant in an inertial frame

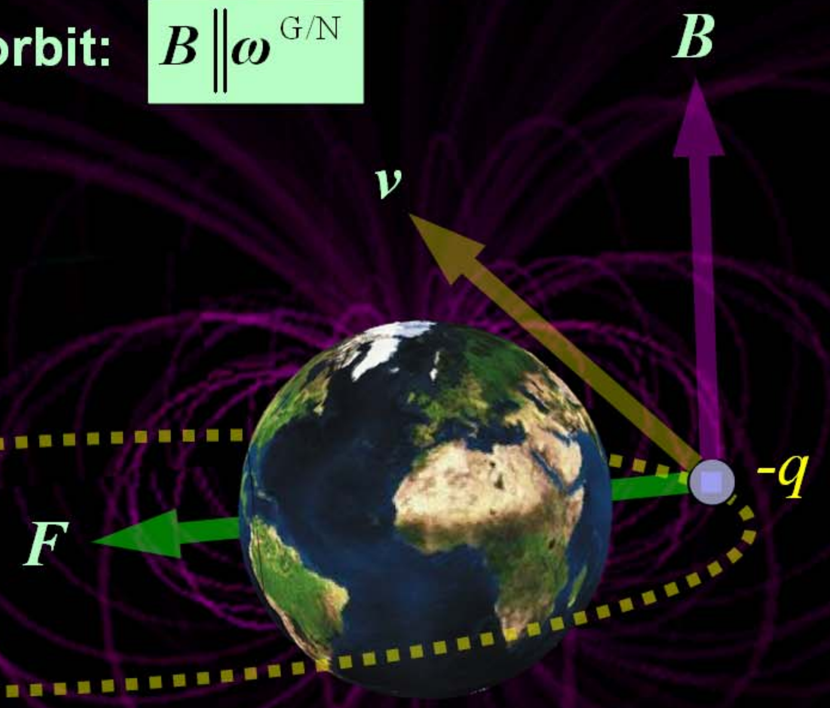
– Consider an equatorial elliptical orbit: $\boldsymbol{B} \parallel \boldsymbol{\omega}^{G/N}$

$$E = -\frac{\mu}{2a}$$

$$\dot{E} = \dot{a}\frac{\mu}{2a^2} = \frac{{}^{N}d}{dt}\boldsymbol{r} \cdot d\boldsymbol{F}$$

...

$$\dot{a} = \frac{qB}{m}\frac{2a}{\mu} r\dot{r}\omega_e$$



An LAO steals a little energy from a planet's rotation, like a flyby steals some from its orbit

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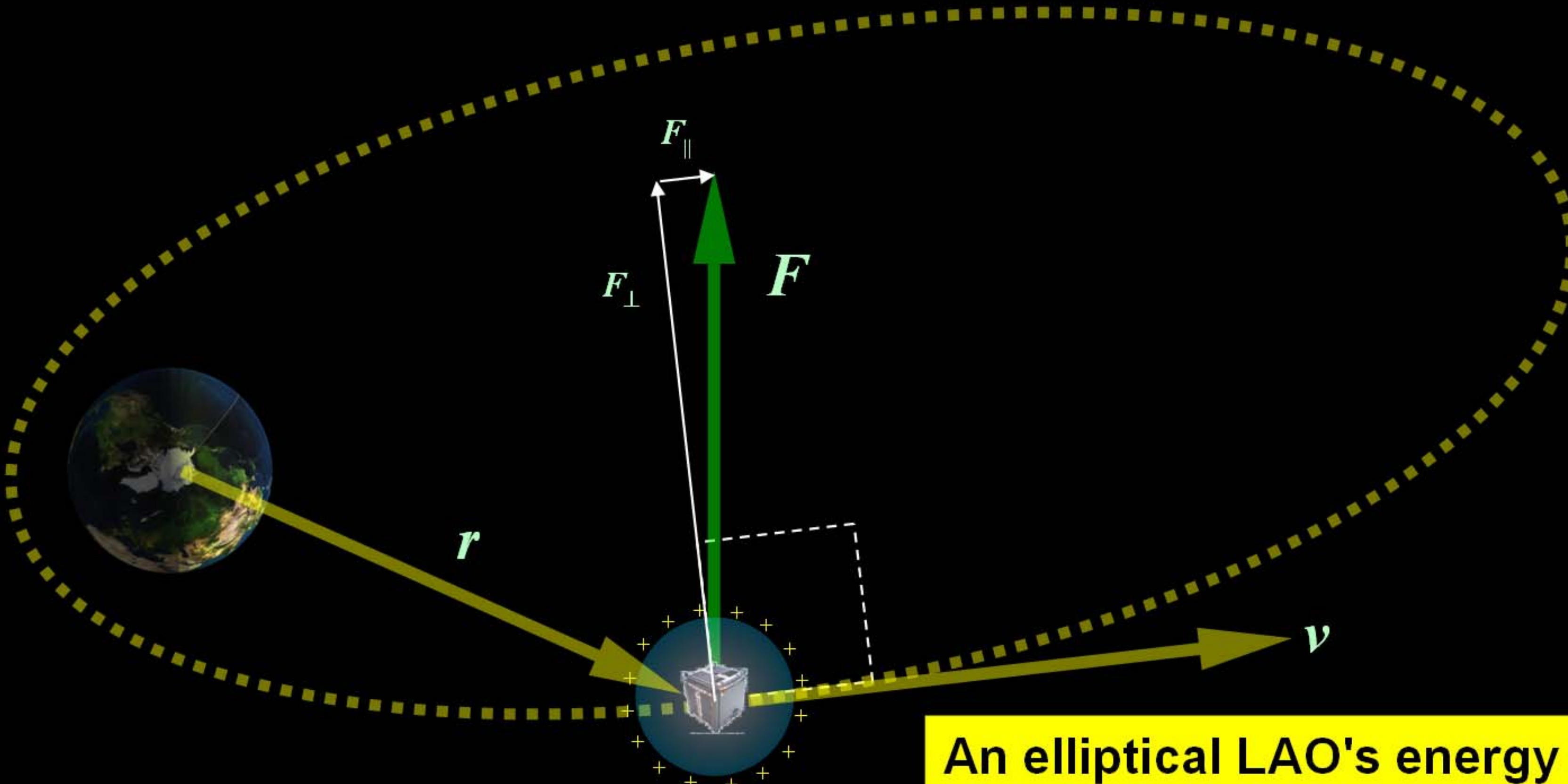
An LAO's energy is not constant in an inertial frame

– Earth's spin imparts a component along *v*, adding energy



An elliptical LAO's energy can grow, leading to Earth escape