Lorentz-Actuated Orbits:

Electrodynamic Propulsion without a Tether

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Overview

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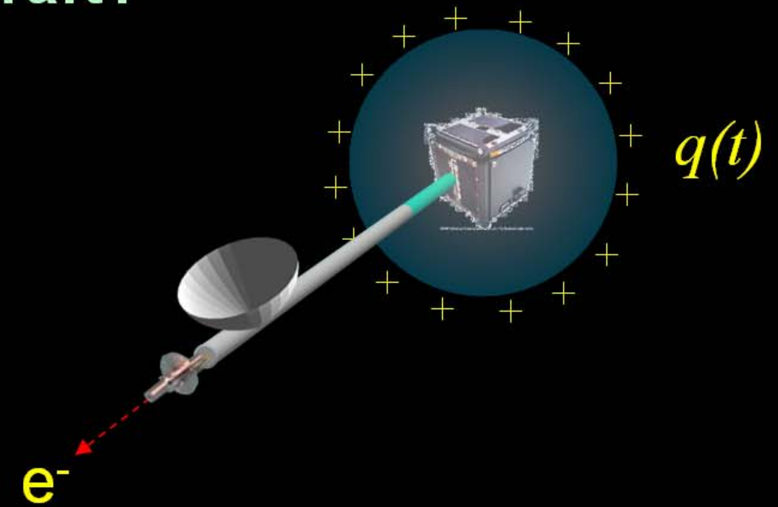
The Big Idea
- Lorentz-augmented celestial mechanics
- Electrodynamics in a rotating frame
- Motivating applications

FAQ: Designing LAO-capable Spacecraft
- Faraday cage concept
- Structural limitations
- Subsystem idiosyncrasies
- Plasma interactions

Some Applications
- Rendezvous
- LAO formations
- Earth escape
- Jupiter capture
- Geosynchronous LEO
- Lunar Free-return

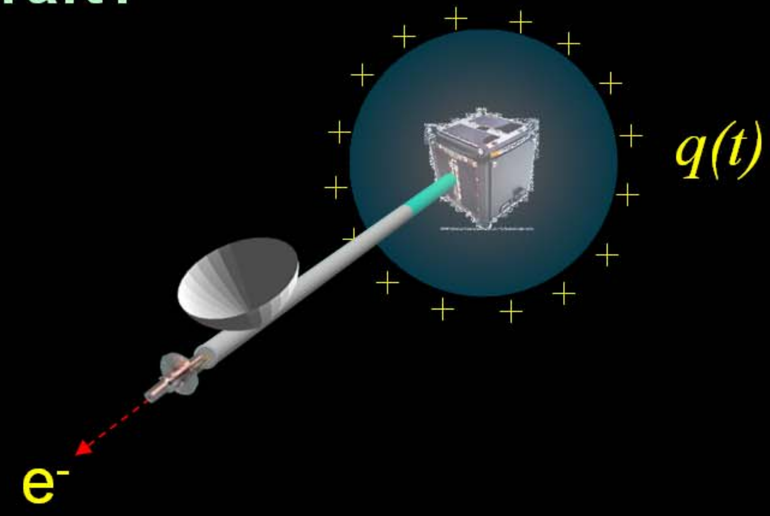
Future Directions and Questions

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



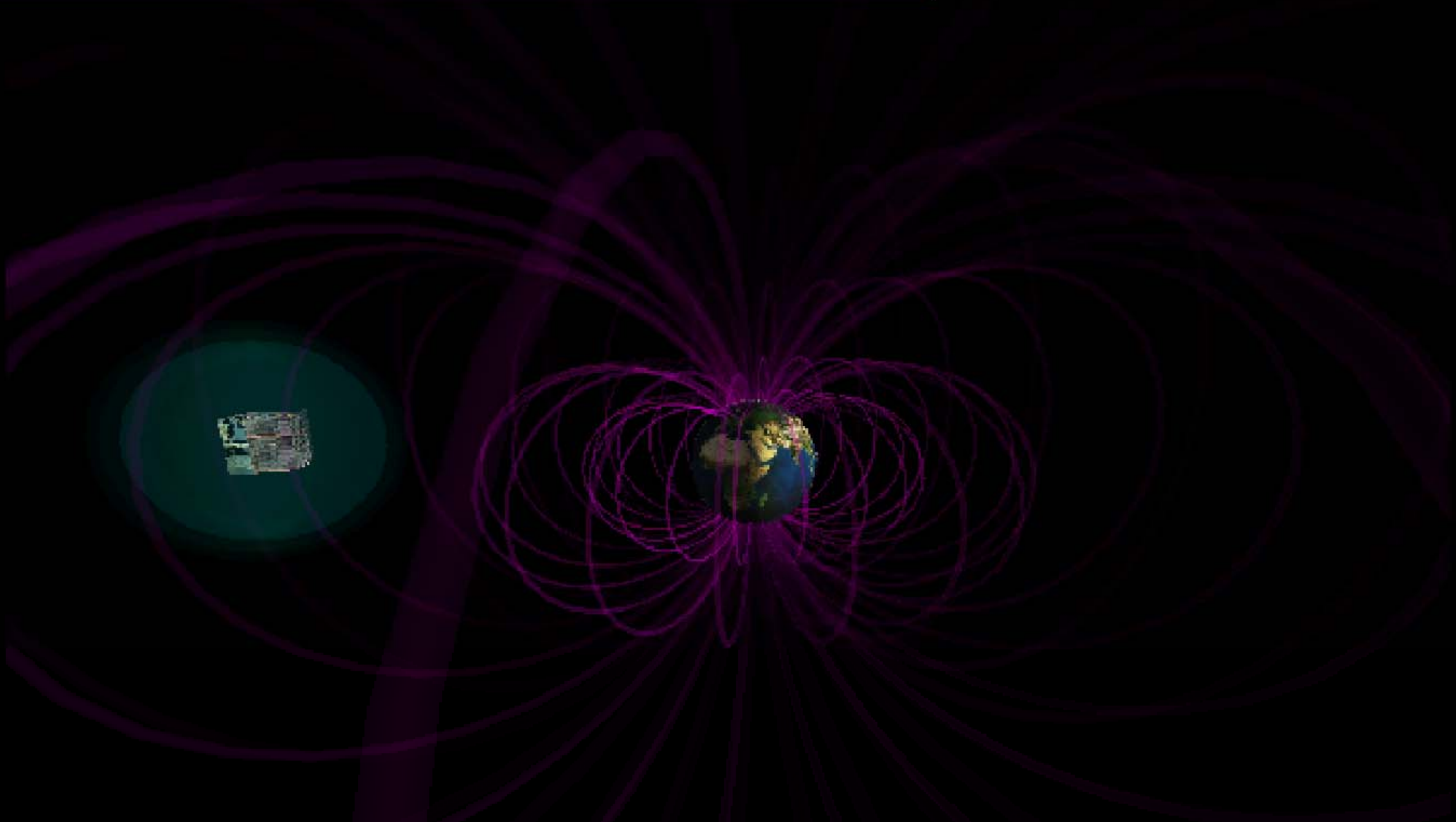
- For example, Burns, Schaeffer, et al.; Cassini, Voyager data
  - Measurements show that Lorentz resonances determine structures in the rings of Jupiter and Saturn
  - Micron-size particles
  - A few volts of potential

The 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: ***J*×*B***
  - Electrons traveling at cm/sec through a conductor
  - This spacecraft's charge *is* a current (high charge at high speed): *q**v***×***B***
  - ***The LAO spacecraft is much more compact than a tether and enables higher-agility attitude motions***

Electrodynamics in a rotating frame



To see the video, use either link:
Low resolution: http://www.mae.cornell.edu/mpeck/SSDS/LAO/lsa_04-Mar-2006_20-23-24_magfield.avi
High resolution: http://www.mae.cornell.edu/mpeck/SSDS/LAO/lsa_04-Mar-2006_21-16-13_magfield.avi

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Electrodynamics in a rotating frame

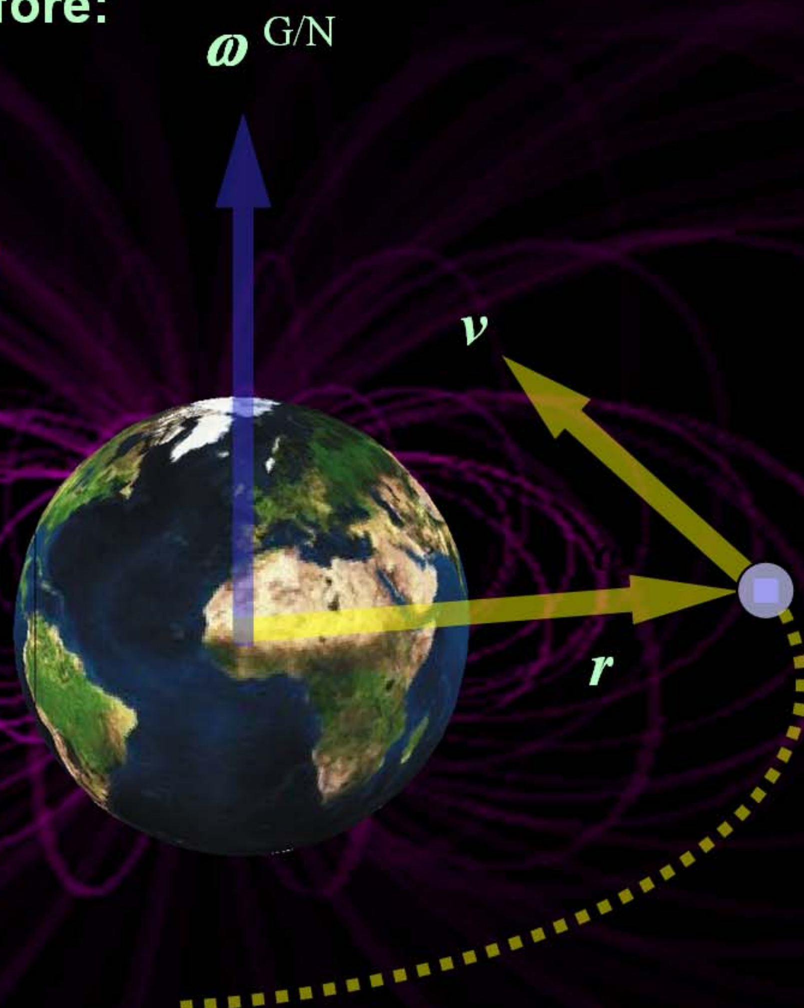
- Lorentz Force, as you've seen it before:

$$F = qE + qv \times B$$

- 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).



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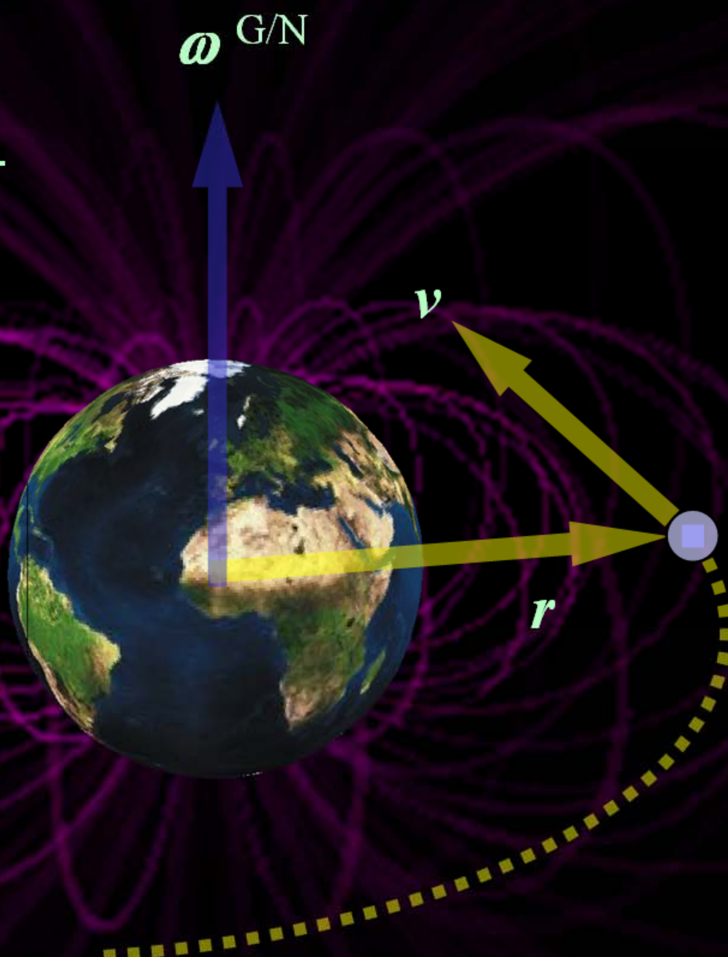
Electrodynamics in a rotating frame

- **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**

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

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

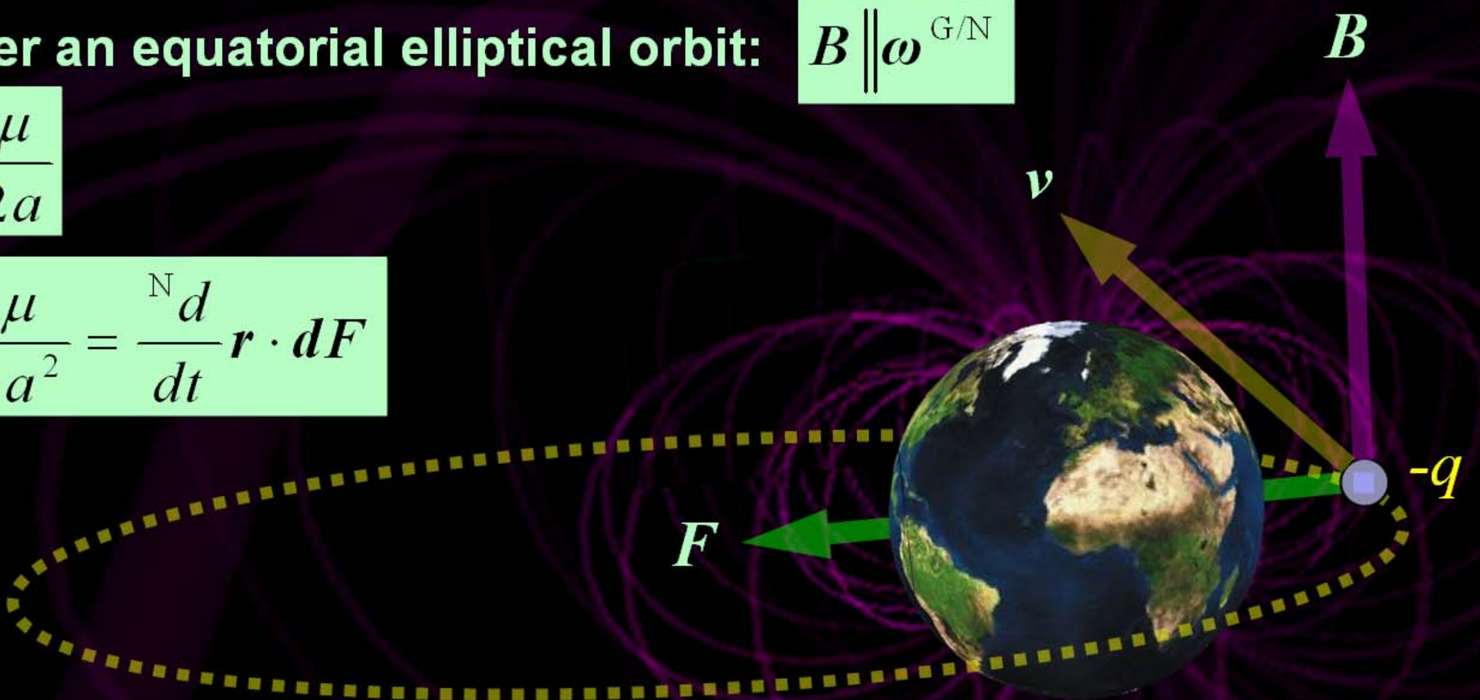
– Consider an equatorial elliptical orbit: $B \parallel \omega^{G/N}$

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

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

...

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



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

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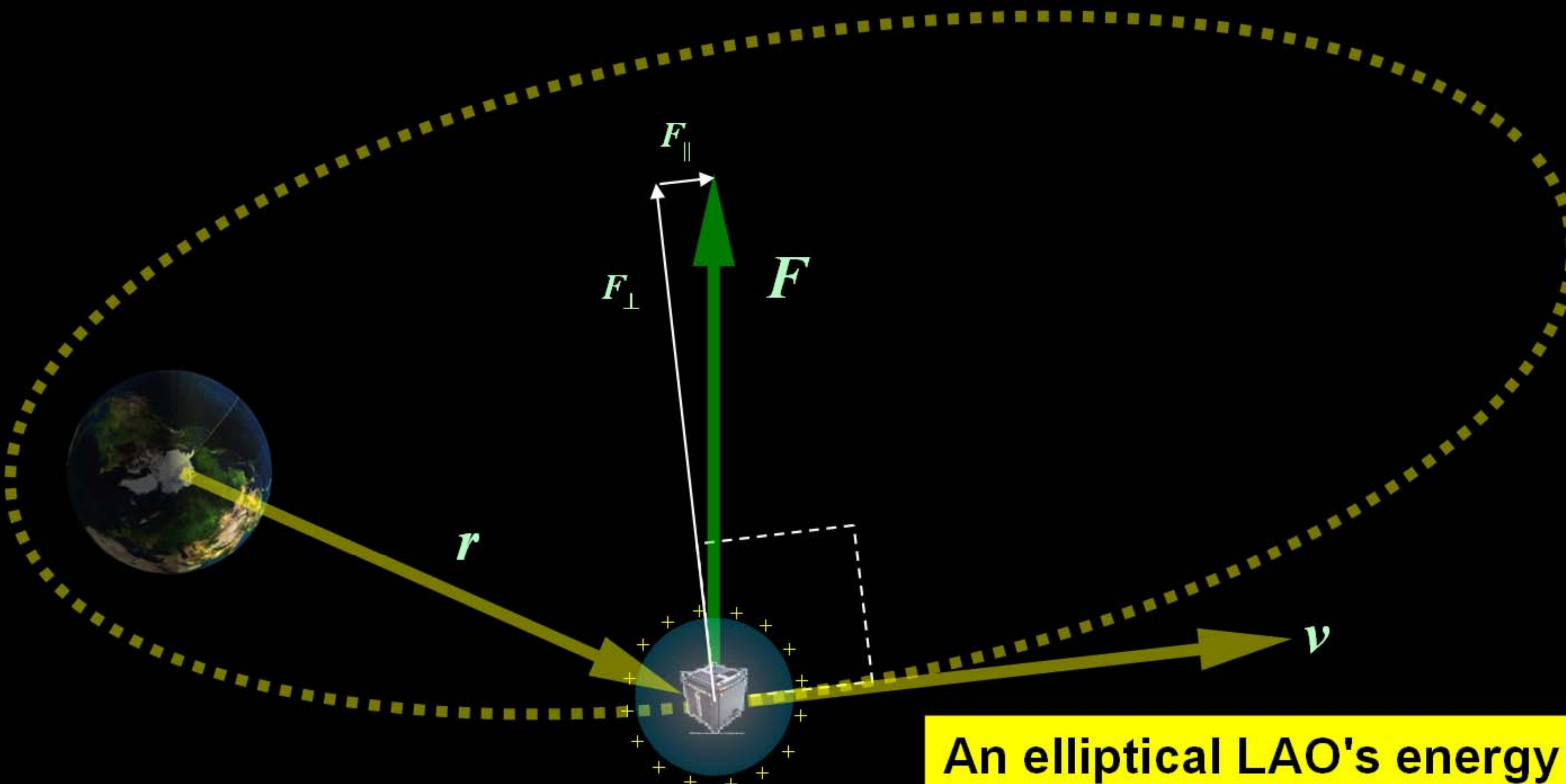
An LAO's energy is not constant in an inertial frame

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



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

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There's *much* more than just Earth escape…

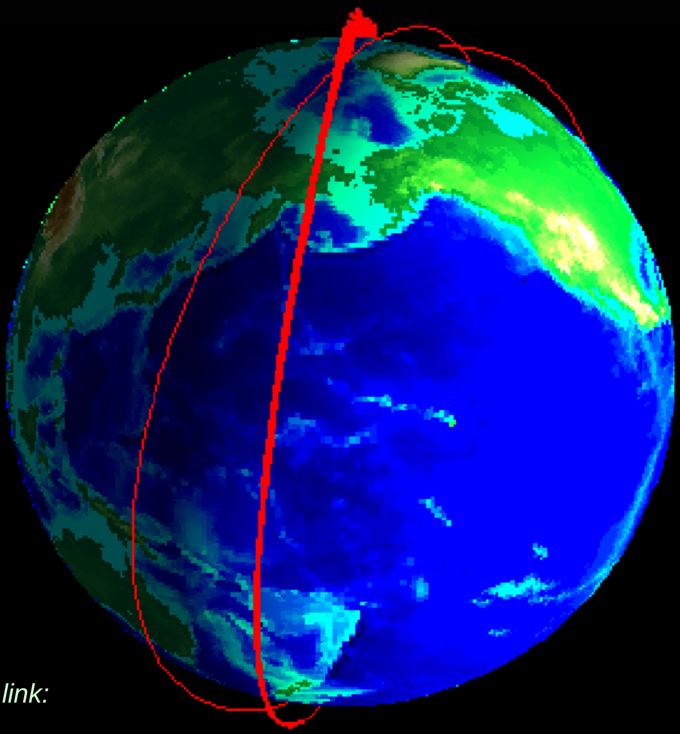
- For example, quickly pre-cessing polar orbits

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

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

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

$$F = qv \times B$$



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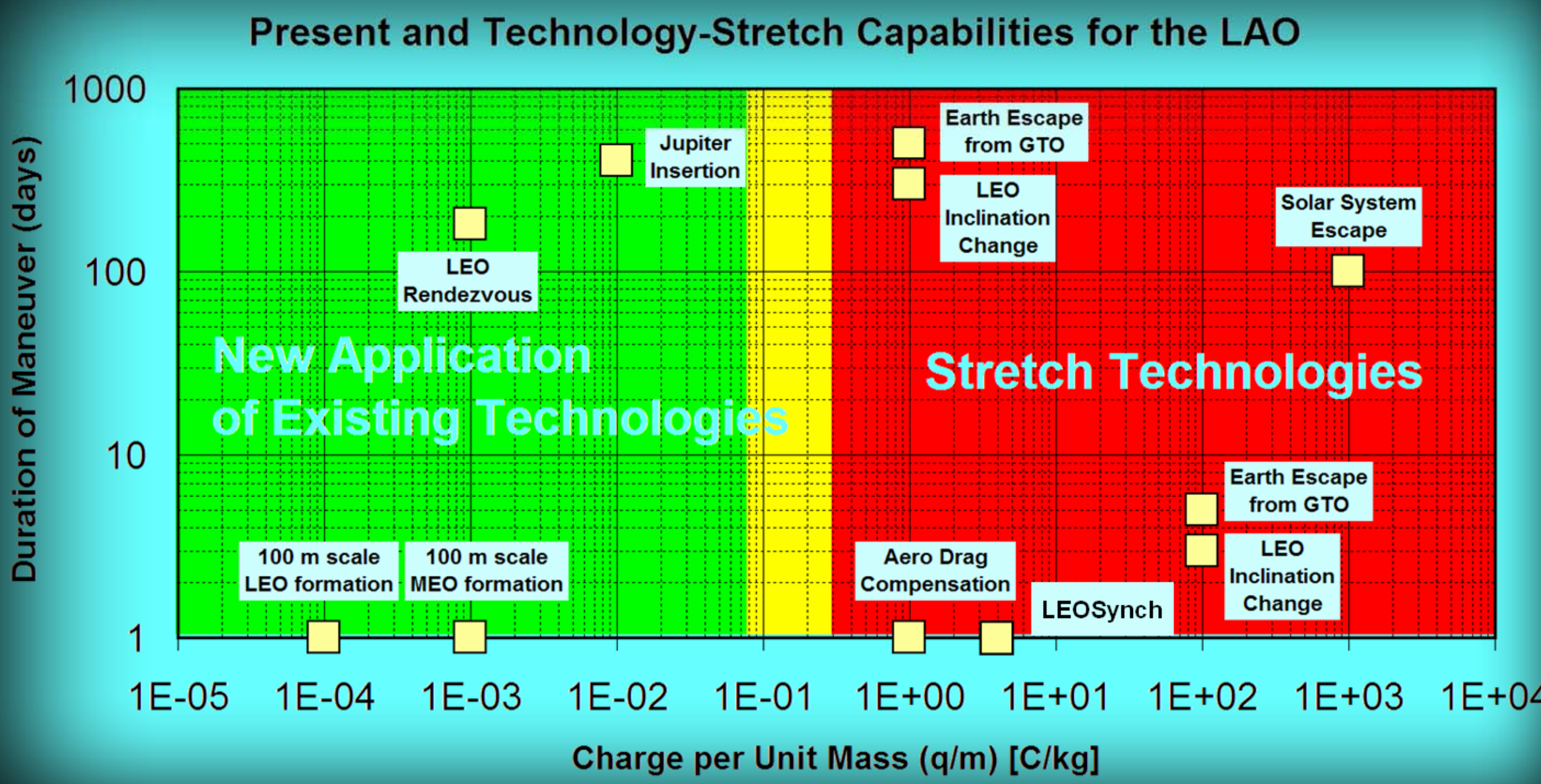
Important Questions

- How much charge do you need?
- How much power does it take?
- What about the Debye sheath?
- How big is the spacecraft?
- How is charge established and maintained?
- What is the impact of this charge on spacecraft subsystems?

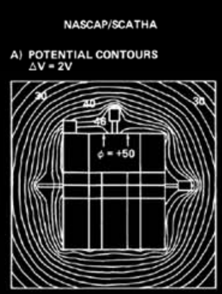
Designing LAO-capable Spacecraft

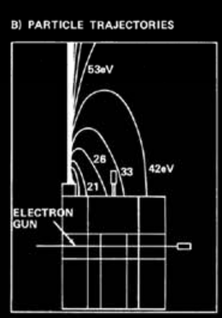
How much charge do you need?



How much power does it take?

- If it weren't for ionospheric plasma, no power--all that would be required is to set the charge and forget it.
- However, discharge via the plasma means a constant current is necessary to maintain a desired potential.
  - From SPEAR I, assuming $\dot{q}(t) = -\alpha(q - q_0) + I_{beam}$, 0.06 W/V at 200-350 km altitude. Much less at higher altitudes (0.001 - 0.0001 W/V at MEO?)
  - Shuttle experiments (SEPAC): 5kV for <100 mA: 0.1 W/V





SCATHA

SEPAC

How much power does it take?

- So, maybe hundreds to thousands of Watts for a system of interest.
- But it all depends on capacitance C
  - High capacitance allows low voltage (maybe floating potential)
  - Low capacitance requires high voltage

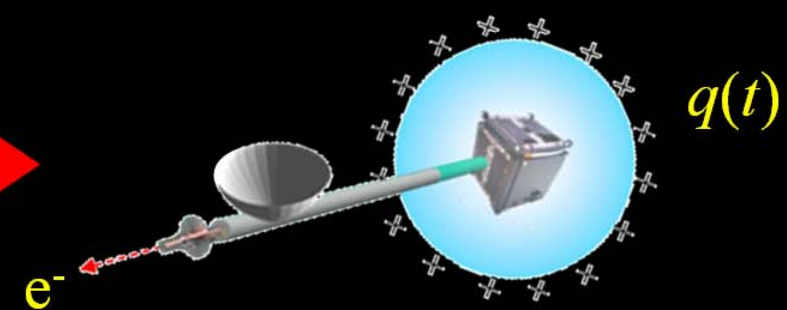
$$q = CV$$

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

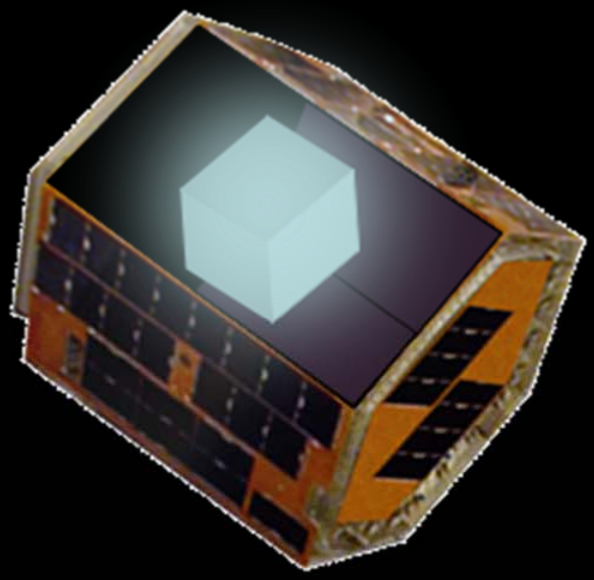
L'Garde Conductive Sphere



Faraday-Cage Capacitor Concept

How is charge established and maintained?

- However, if a high-capacitance solution is found, e.g. one that maintains high charge at the spacecraft floating potential
  - No Debye sheath?
  - No power required?
- The Unobtanium capacitor
  - Key research target
- Pocket



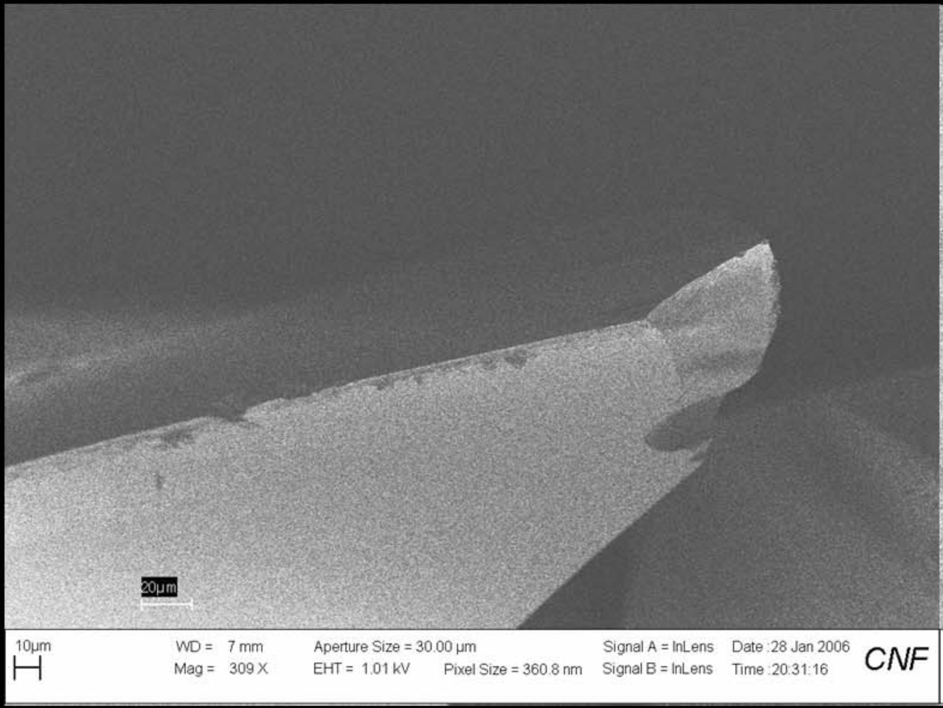
How is charge established and maintained?

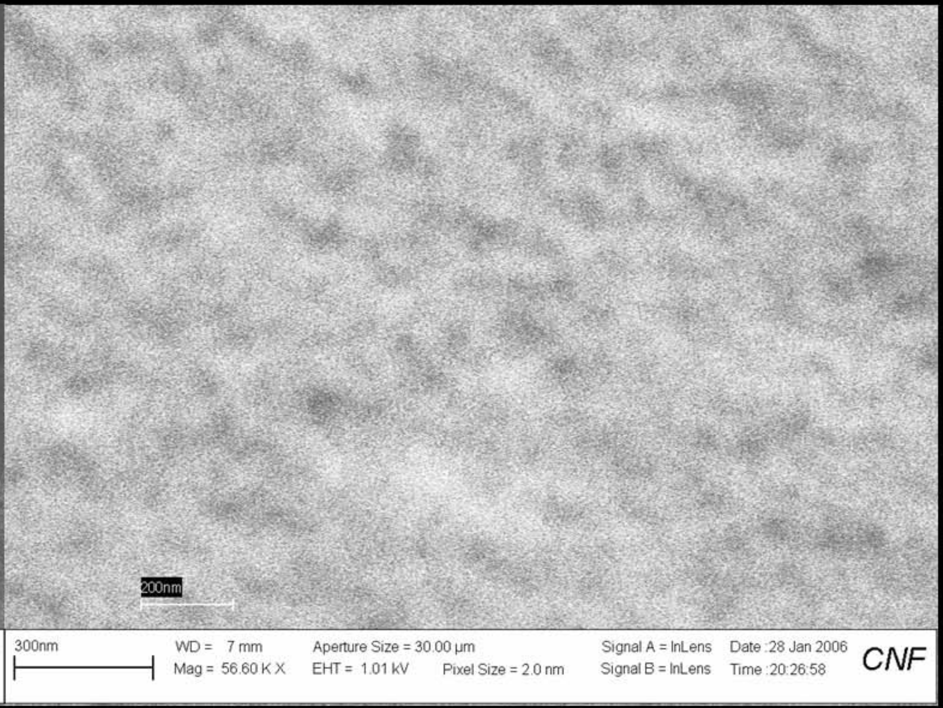
- Carbon Nanofoam
  - Relatively new, semiconductive allotrope of pure carbon; sometimes called "carbon aerogel."
  - 400 m^2/g due to nanoscale porosity and convolutions
  - 30 F/g (30,000 C/kg at 1 V?)
  - High charge, low potential (q=CV)
- Spacecraft Architecture:
  - Nanofoam resides on spacecraft surface
  - Plasma interactions charge it to the floating potential
  - Manipulate voltage through conductive connections to other materials with varying dielectric constants?

How is charge established and maintained?

– SEM Photographs of Nanofoam

- Electron beam was deflected due to high charging of sample





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)
  - Nanofoam 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…)

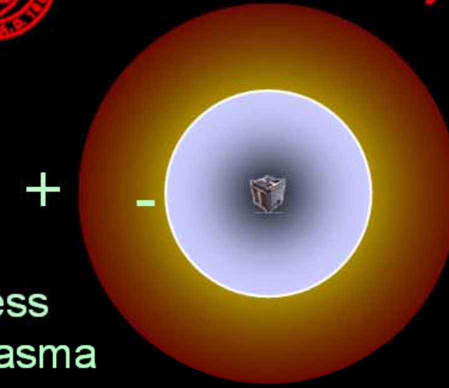
How big is the spacecraft?

– The key sizing parameter is charge per unit mass (*q/m*), which is proportional to the acceleration (Δv) available

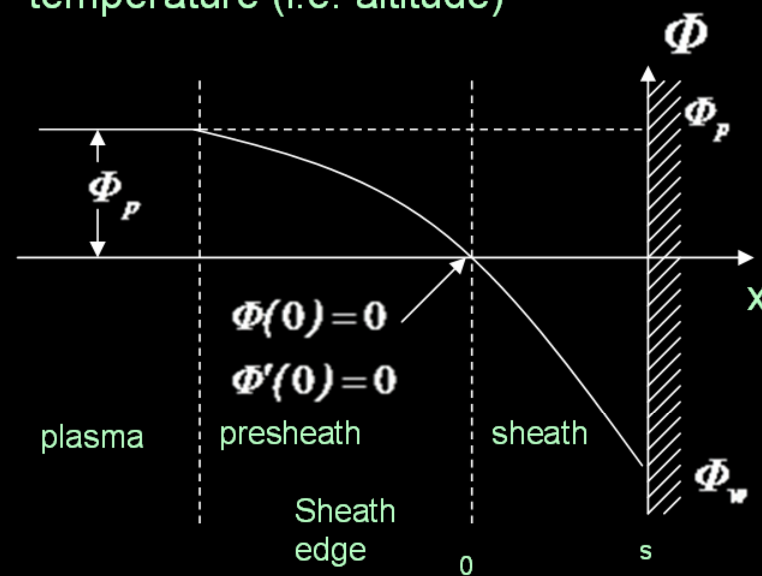
– Off-the-shelf capacitors are not generally useful

– For a spherical spacecraft surrounded by plasma,

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

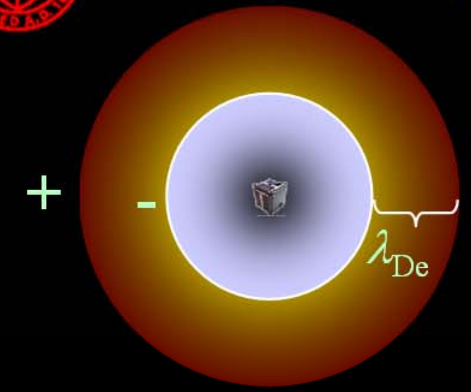


Sheath thickness depends on plasma temperature (i.e. altitude)



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

Interactions with the Debye Sheath

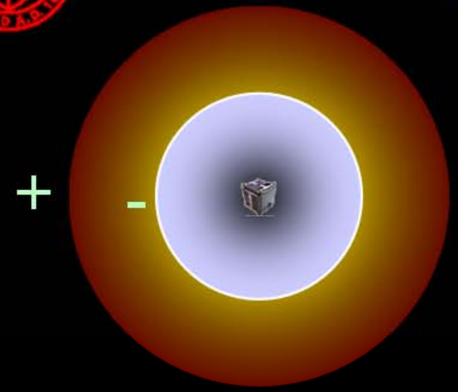


- Stationary plasma forms an oppositely charged sheath around a charged body
  - Shields electric fields (no Coulomb interactions)
  - Thickness (λ_{De}) is 1 cm - 10 m in Earth orbit
- Benefits
  - Huge increase in capacitance over the vacuum case
  - Balances electrostatic pressure (sphere's material tensile strength does not limit charge!)

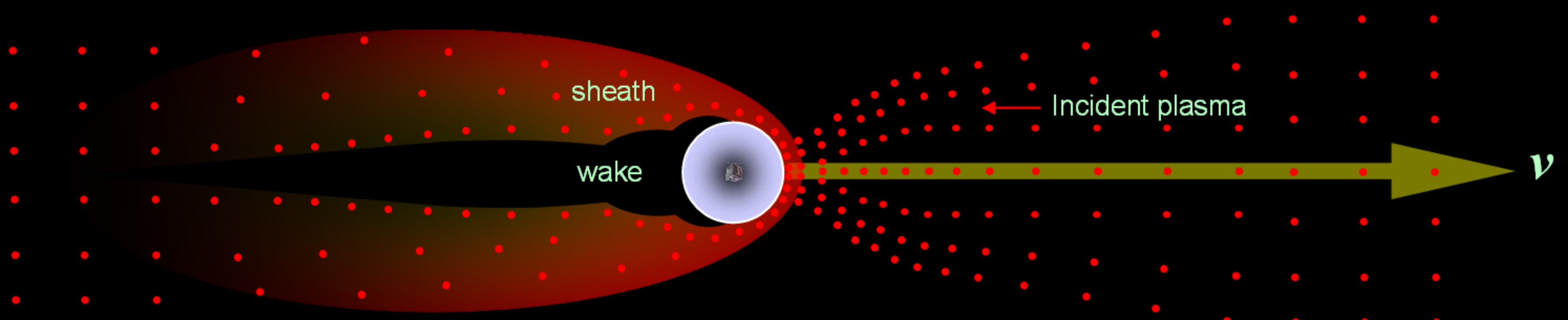
$$C \approx 4\pi\varepsilon_0 \frac{R\left(R+\lambda_{De}\right)}{\lambda_{De}}$$

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

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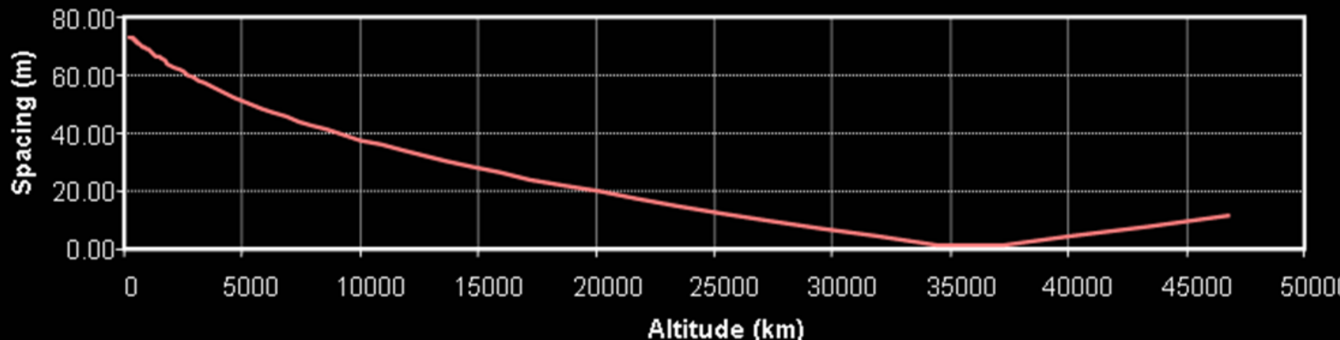
Attempt to bound worst-case design metrics

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

LAO Formations

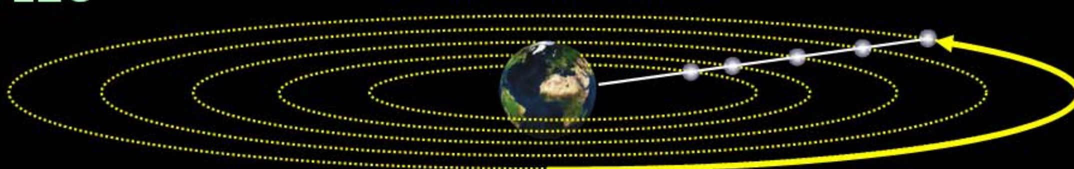
$$r = \sqrt[3]{\frac{1}{\omega^2}\left(\mu - \frac{q}{m}(\omega - \omega_e)B_0 r_0^3\right)}$$

– 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 (1000 W)
- r=3 m sphere



Some Applications

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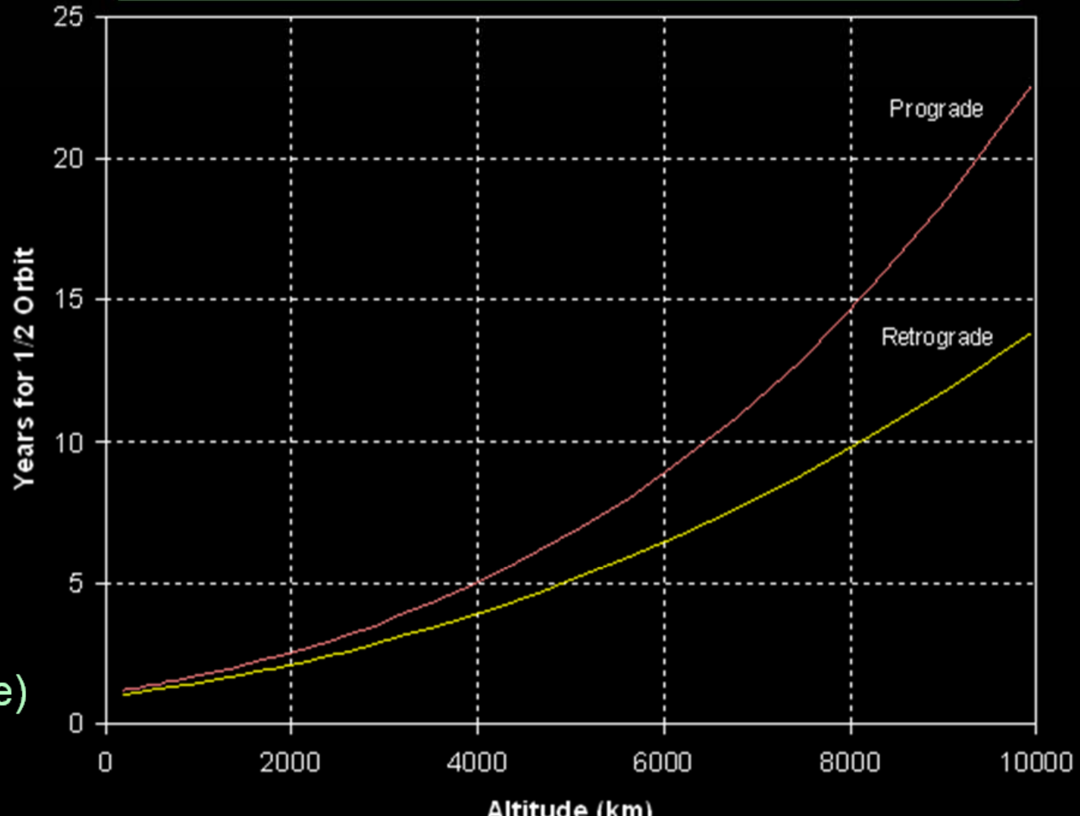
Rendezvous

- 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 E is greater.

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

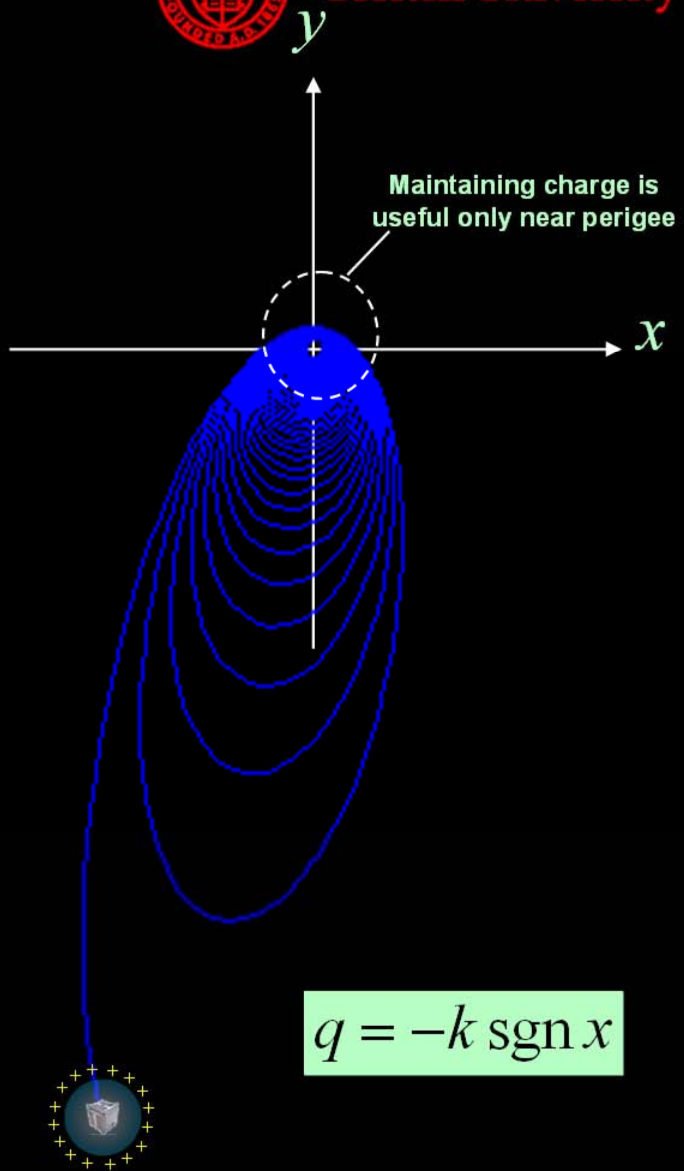
$$\omega = -\frac{q}{m}B_0\frac{r_0^3}{r^3} \pm \frac{\sqrt{\left(\frac{q}{m}B_0 r_0^3\right)^2 + 4r^3\left(\mu + \frac{q}{m}\omega_e B_0 r_0^3\right)}}{2r^3}$$



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

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 the nanofoam.
- Specs for a sphere:
  - 100 kg spacecraft
  - 20 MV potential (2MW power bursts)
  - r=50 m sphere



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

Some Applications

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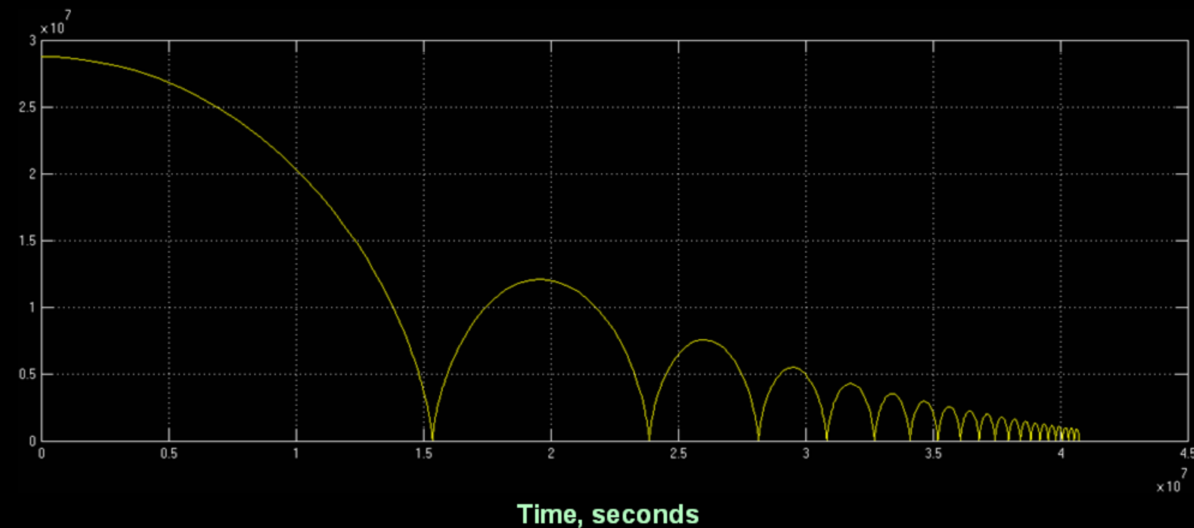
Jupiter Capture

- 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

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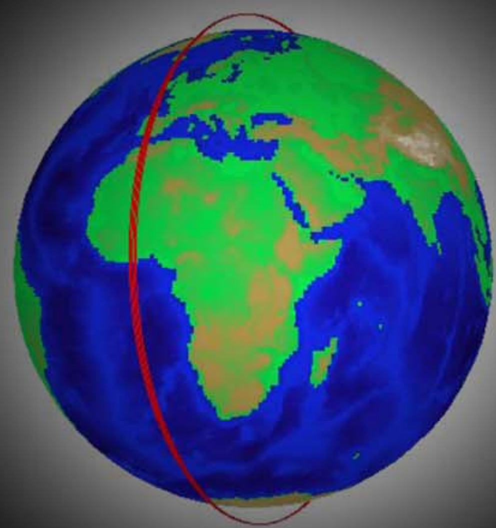
Geosynchronous LEO Imaging Spacecraft

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

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



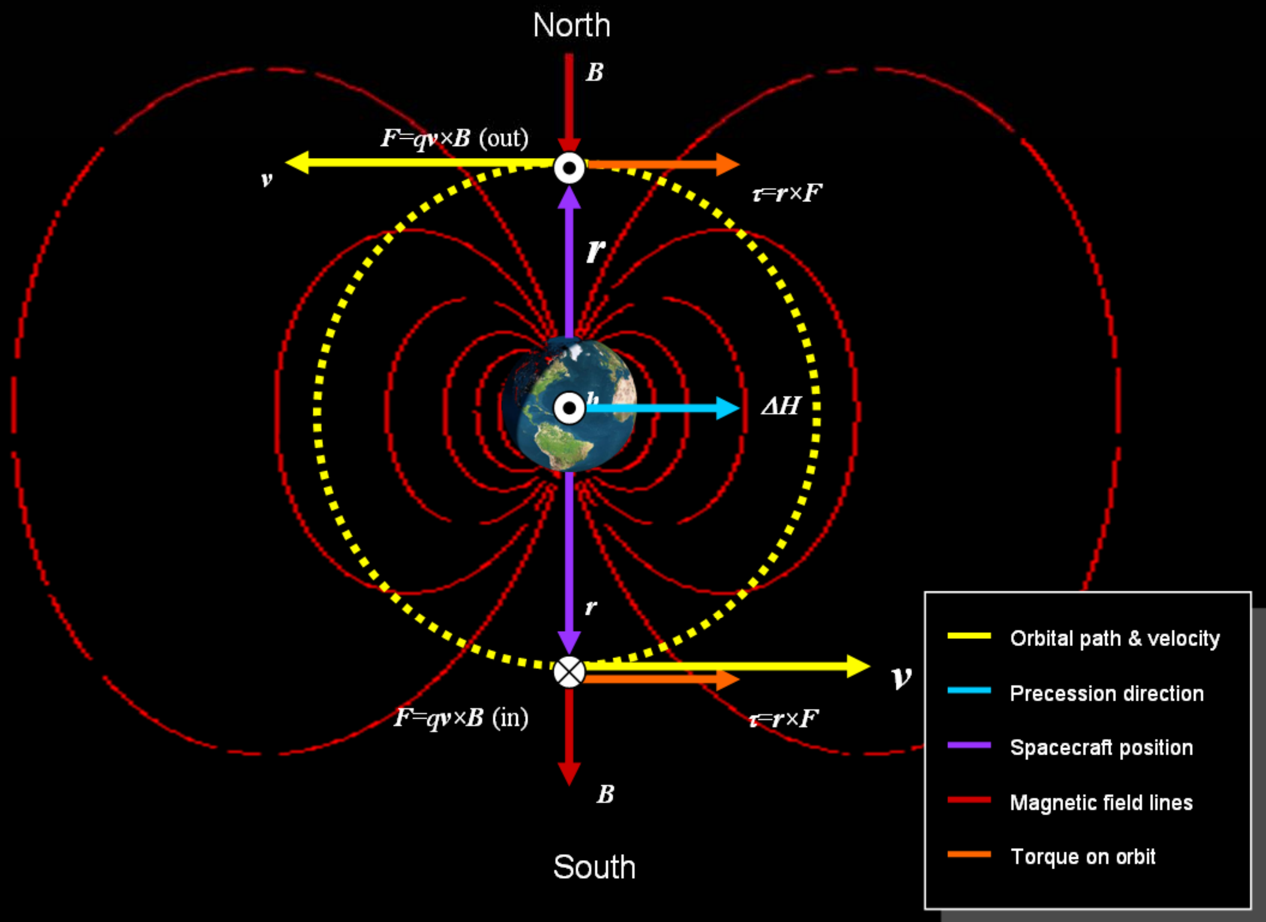
- Specs for a sphere:
  - 100 kg spacecraft
  - 5 MV potential (500 kW)
  - r=75 m sphere

Geosynchronous LEO Imaging Spacecraft

$$F = qv \times B$$

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

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



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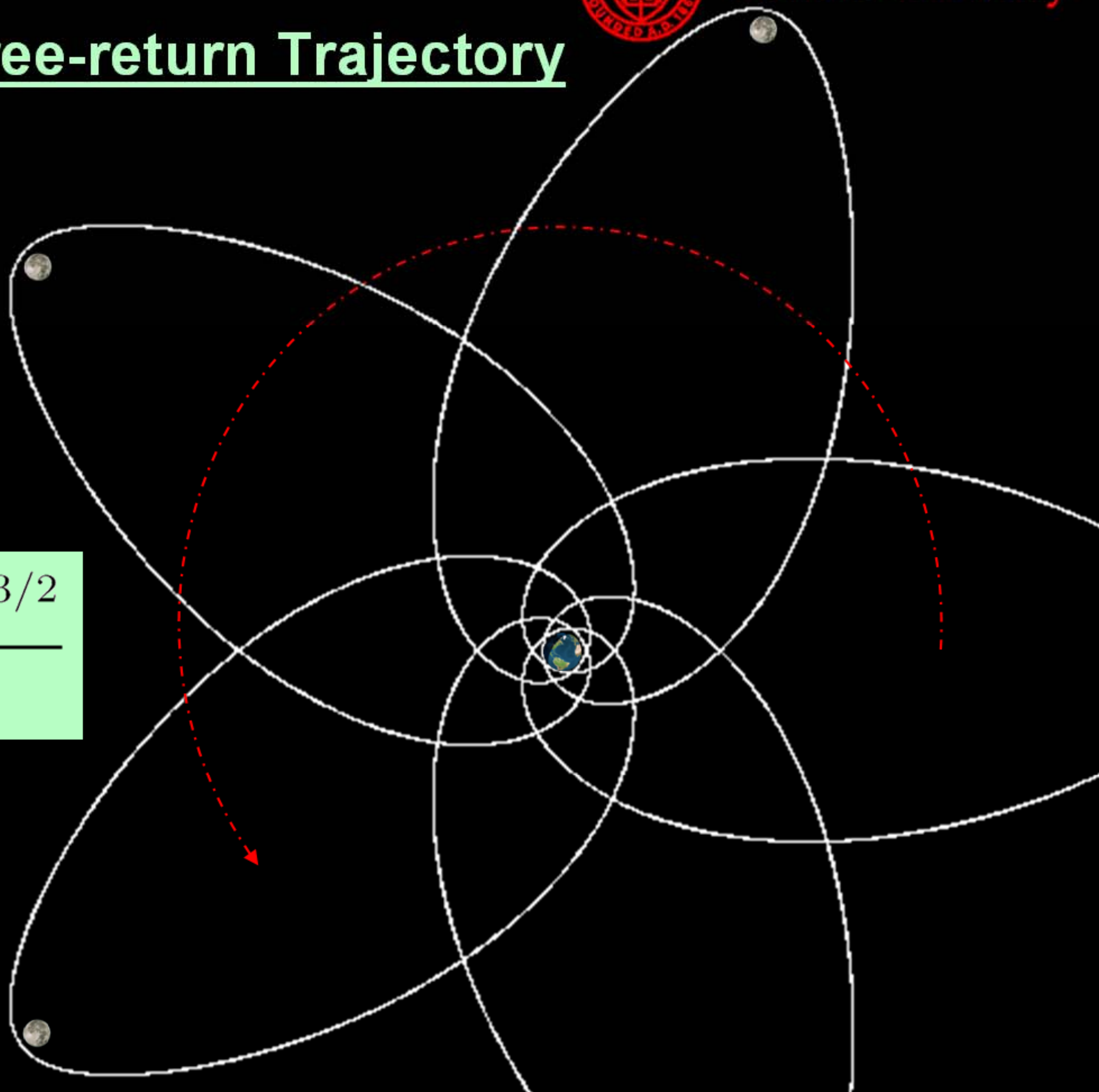
Continuous Lunar Free-return Trajectory

- 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



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 because of specific-power needs
  - A technology path exists for extraordinary far-term applications

– **The plasma environment can be managed**
  - The Debye sheath helps by increasing capacitance and lowering (or eliminating) electrostatic pressure
  - The Debye 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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- **Perform more detailed hardware evaluation**
  - The spherical conductive shell concept solves many problems, including ESD.
  - Carbon nanofoam tests continue
  - Hairy spheres
  - ISS test of nanofoam? Sounding rocket opportunity with AFRL? Cubesat demo?
- **Perform plasma simulation and scaled testing**
  - Detailed evaluation of phenomena at high potentials, including effects such as surface imperfections.
  - Modeling