Electrodynamic Tether at Jupiter

1. Capture operation and constraints

Juan R. Sanmartin and M. Charro, Universidad Politecnica de Madrid

E. Lorenzini , University of Padova,
H. Garrett , Jet Propulsion Laboratory / NASA

C. Bramanti and C. Bombardelli, European Space Agency / ESTEC

European Geosciences Union / General Assembly 2007

Galileo: A successful but handcuffed mission

* High wet-mass for chemical propellant

⇒ reduced orbital manoeuvring after capture

⇒ kept scientific payload to a few percent in mass

Jointly with launcher limitations led to protracted trip, required GAs

* RTGs was weak power source // Flybys took long times

* Further exploration of *Jupiter / moons* faces issues on

power, propulsion, trip times, radiation

NASA's approaches to the challenge:

* *Europan Orbiter*: Kept RTG’s, chemical propulsion. But

no-GAs (direct) trip + moon- GAs for orbiting *Europa*

* *JIMO* / *Prometheus* 1: Chemical propulsion, RTG’s, GAs off

Nuclear reactor for power, and for powering electrical-thrusters

EO cancelled in Phase B / *JIMO* deferred indefinitely

* *JUNO* (Polar Orbiter): Back to (5-year) trip, chemical propulsion

But, RTG’s dropped, solar cell arrays used for power

Further NASA planning:

* JPL Studies (*Europa Geophysical Explorer*, *Europa Explorer*)

\+ *OPAG* planning:

GAs for both indirect trip and moon-mediated capture by Europa,

3-month stay (3 Mrad *Si* radiation dose)

* Other moons: *Jovicentric Orbiter* for 50 *Io* flybys (< 2 Mrad *Si*)

* *Ganymede Exploration Orbiter* + *E*3 *Orbiter with Probes*

GEO: 5-year *Europa* observer + relay for *E3OP* (1month at *Europa*)

ESA's approach to challenge:

* *Jovian Minisat Explorer*: Indirect trip, solar-cell power

chemical propulsion (+ SEP backup),

* Develop *LILT* - *GaAs* cells with solar concentrators

If solar program failed → problematic reversion to RTG's

* S/C split → *Jovian Europan Orbiter* + *Jovian Relay Satellite*

GAs to get *JEO* to *Europa*, *JRS* to Jovian 3:1 resonance orbit

JRS serves as relay for *JEO* (like *GEO* for *E3OP*)

New approach: Tapping Jupiter’s rotational energy

* No RTGs, no solar power, no NEP

Spare use of GAs, chemical propulsion

* Positions of perijove, apojove in elliptical orbits

relative to equatorial stationary orbit of radius $a_s \equiv (\mu_p / \omega_p{}^2)^{1/3}$

$\Rightarrow$ make Lorentz force induced on ED-tether be *drag* / *thrust*

always reduce mechanical energy, *generate power*

a_s - orbit has maximum of mechanical energy in Spin/Orbit interaction

* Small Satellite (Planet spin, Orbital motion contribute to

energy $\varepsilon(\omega_p, a)$, *angular momentum* $H(\omega_p, a) = H_0$

$\Rightarrow$ $\varepsilon(a)$ can present 2 rigid-body motion ($\Omega_{orb} = \omega_p$) extrema

* Rigid-body motion at $a(\varepsilon_{min})$ (farther from planet) is stable

Rigid-body motion at $a(\varepsilon_{max})$ is unstable

Any dissipation would move satellites away from $a(\varepsilon_{max})$

* For artificial satellites, $a[\varepsilon_{max})] = a_s$

Power, Drag / Thrust at ED-Tethers

$$\bar{E}(tether\ frame) - \bar{E}(plasma\ frame) = (\bar{v}_{orb} - \bar{v}_{pl}) \wedge \bar{B} \equiv \bar{E}_m$$

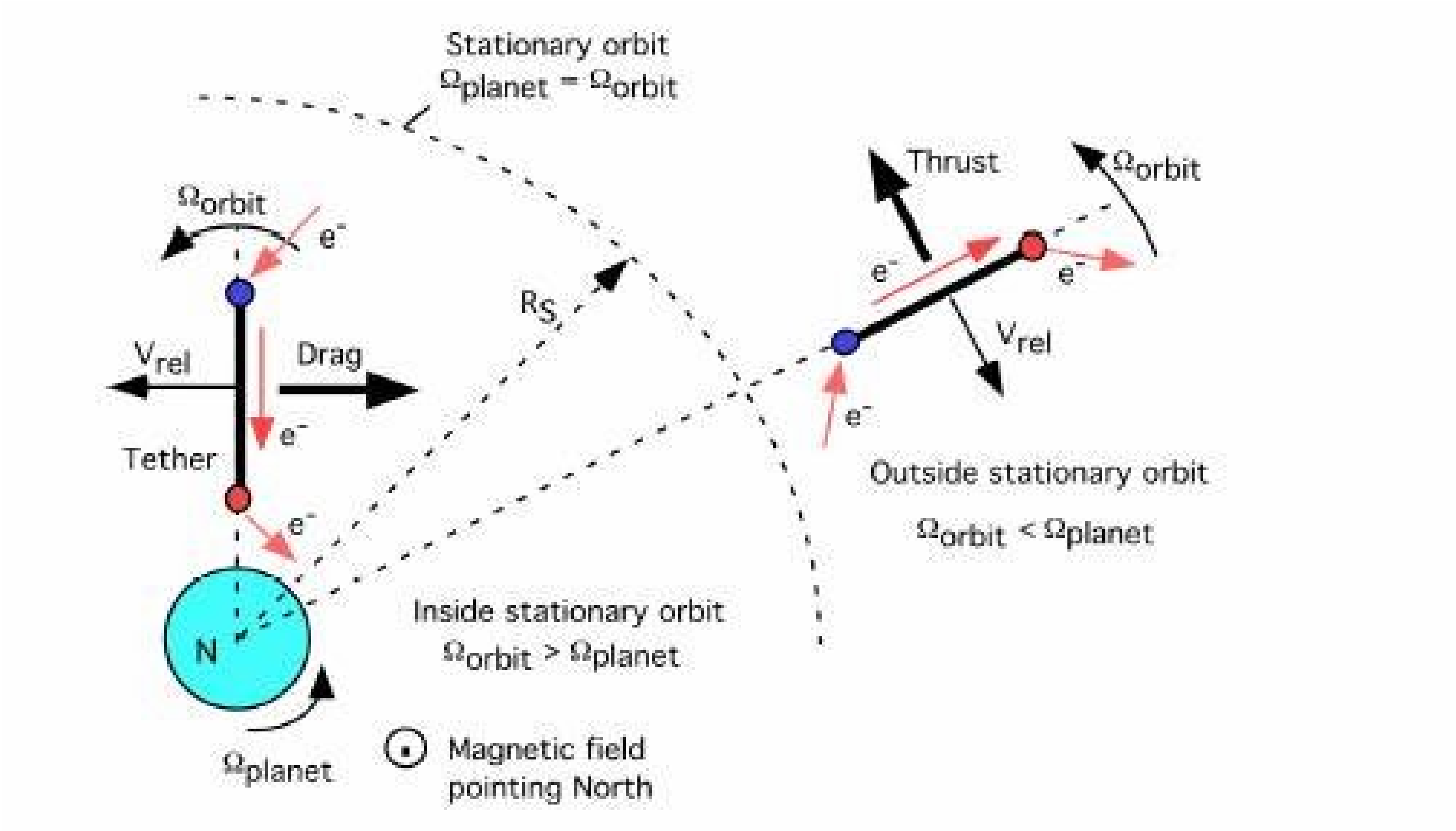
Outside tether: $\bar{E}\,(tether\ \ frame) \;\;\approx\;\; \bar{E}_m$

Inside tether: $\bar{E}\,(tether\ \ frame) \;=\; \bar{I}\,/\sigma_c A_{cs}$

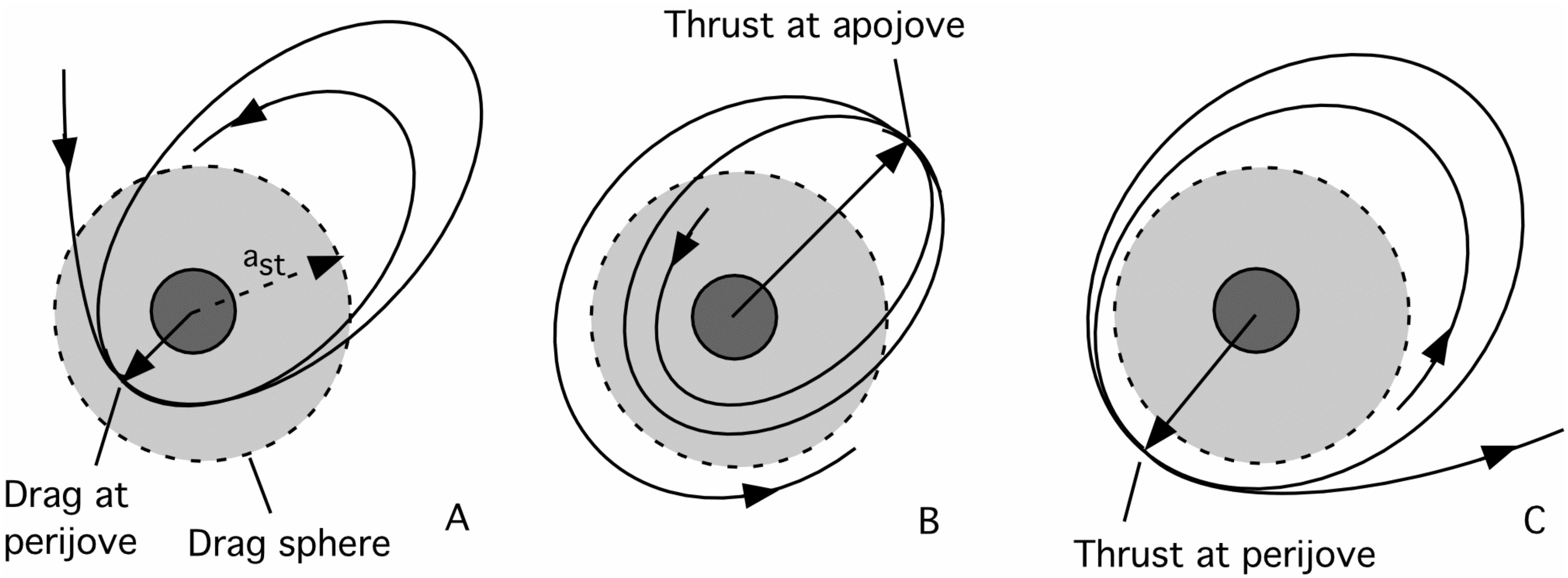
* Lorentz force: $L\,\bar{I} \wedge \bar{B} \qquad (\bar{I} \bullet \bar{E}_m \;>\; 0)$

$$\Rightarrow \;\; (L\bar{I} \wedge \bar{B}) \bullet (\bar{v}_{orb} - \bar{v}_{pl}) \;=\; -L\bar{I} \bullet \bar{E}_m \;<\; 0$$

Thrust <u>if</u> $\bar{v}_{orb}$ opposite $\bar{v}_{orb} - \bar{v}_{pl}$ ($a > a_s$, eastward Earth orbits)


Stationary orbit
Ωplanet = Ωorbit
Ωorbit
e⁻
Thrust
Ωorbit
e⁻
e⁻
RS
Vrel
Drag
Vrel
e⁻
Tether
e⁻
e⁻
Outside stationary orbit
Ωorbit < Ωplanet
N
Inside stationary orbit
Ωorbit > Ωplanet
Ωplanet
Magnetic field
pointing North

* An ideal free-lunch tour of the Jovian System:



ED-tether is kinetic mechanism to reduce spin/orbit energy

But performance heavily dependent of ambient conditions

* Thrust requires corotating dense plasma beyond a_s

For Jupiter, $a_s / R_p \propto (\rho_p / \omega_p^2)^{1/3}$ is 1/3 the Earth value

Magnetic field B at surface is 10 times greater

$\Rightarrow$ Jovian plasmasphere reaches, corotates, beyond a_s

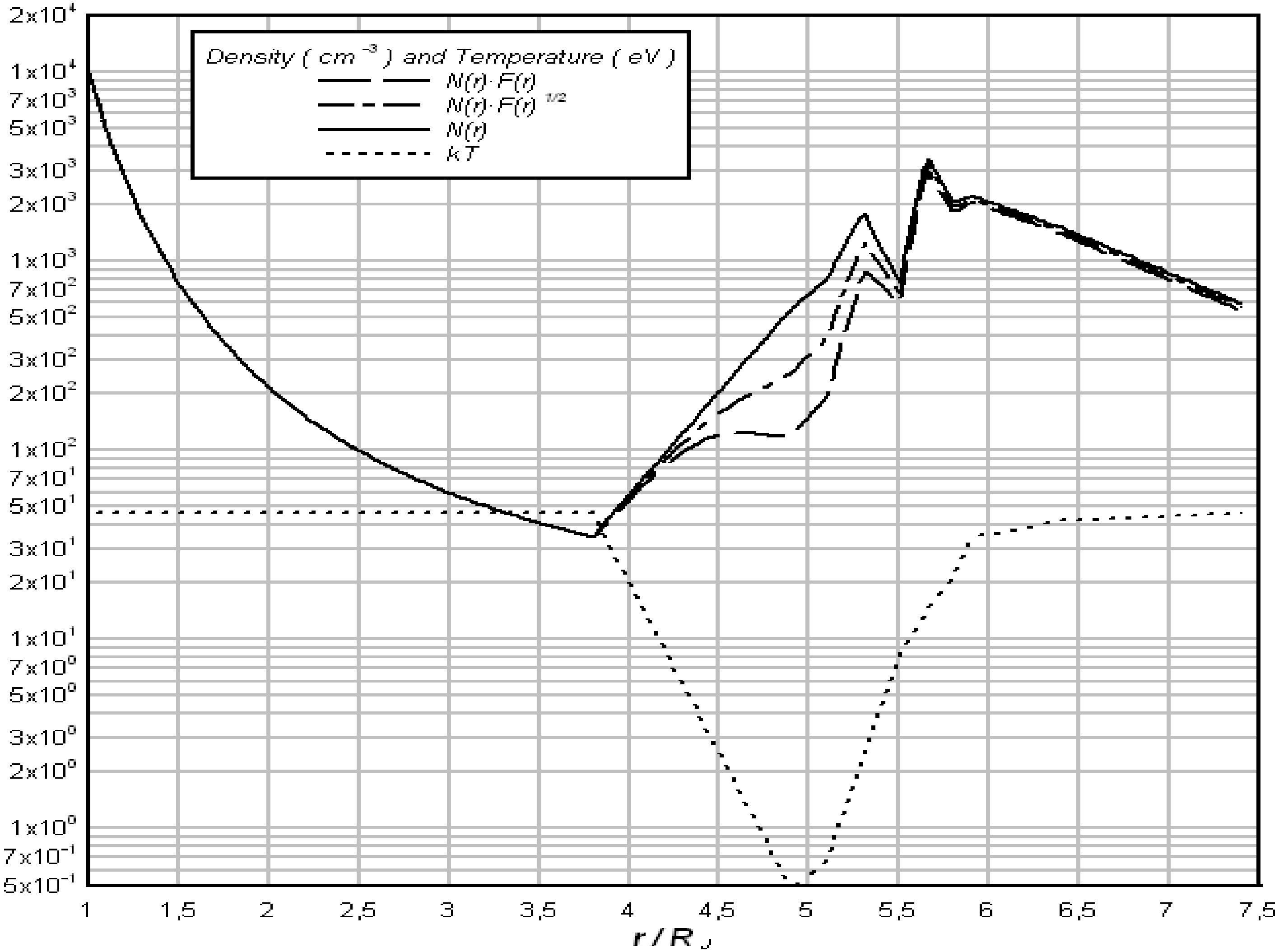
* Moon *Io* at 1:2 resonance with *Europa*,

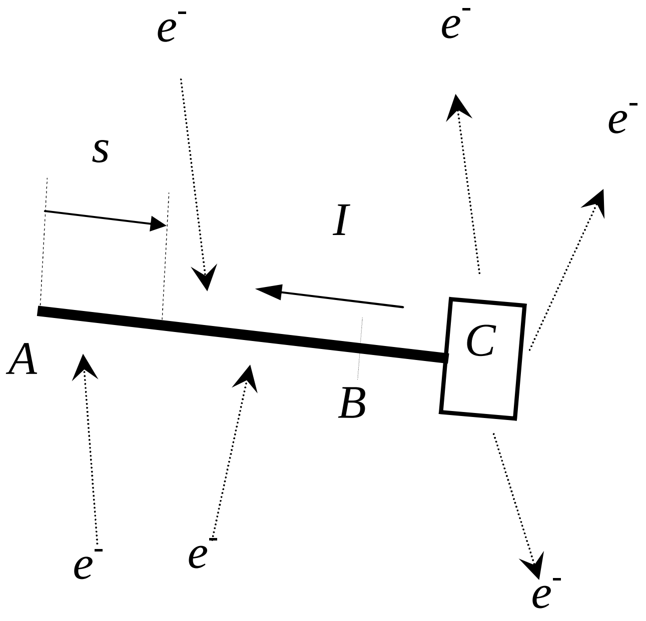
10 times closer to Jupiter than *Moon* to Earth

$\Rightarrow$ Extreme tectonics / volcanism $\Rightarrow$ 1 Ton/s (O, S) eject

$\Rightarrow$ Fast corotating plasma-torus from plasmasphere to *Europa*

Drag / Thrust only applied in plasmasphere / torus


Density (cm $^{-3}$) and Temperature (eV)
N(r)·F(r)
N(r)·F(r) $^{1/2}$
N(r)
kT
2x10⁴
1x10⁴
7x10³
5x10³
3x10³
2x10³
1x10³
7x10²
5x10²
3x10²
2x10²
1x10²
7x10¹
5x10¹
3x10¹
2x10¹
1x10¹
7x10⁰
5x10⁰
3x10⁰
2x10⁰
1x10⁰
7x10⁻¹
5x10⁻¹
1
1,5
2
2,5
3
3,5
4
4,5
5
5,5
6
6,5
7
7,5
r / R_J



Sketch of bare-tether operation.   Bias negative to the right of B.

Electrons collected on anodic segment AB.   Ion collection on cathodic segment BC negligible.

Electrons ejected at hollow cathode C.   Hollow cathode at end A   off.

- Thin bare tape ($L >>$ width $w >>$ thickness h) lighter than round wire

collects electrons as giant probe/OML regime

OML conditions limit w but anodic segment is 10's km long

- Two bounds on length-averaged current

$$I_{av} \leq \frac{2}{5} \times \frac{2wL}{\pi} \times eN_e \times \sqrt{\frac{2eE_mL}{m_e}}$$

(no ohmic-effects)

$$I_{av} \leq \sigma_c E_m wh$$

(ohmic-effects limit)

- Little expellant consumed in ejecting electrons at Hollow Cathode

* Hohmann-like transfer from Earth barely hyperbolic

$$e_h - 1 = \frac{v_\infty{}^2 r_p}{\mu_J} \approx \frac{M_S}{a_J}\frac{r_p}{M_J} \times \left(1 - \sqrt{\frac{2a_E}{a_E + a_J}}\right)^2 \approx 0.018\frac{r_p}{R_J}$$

Make post-capture orbit barely elliptic

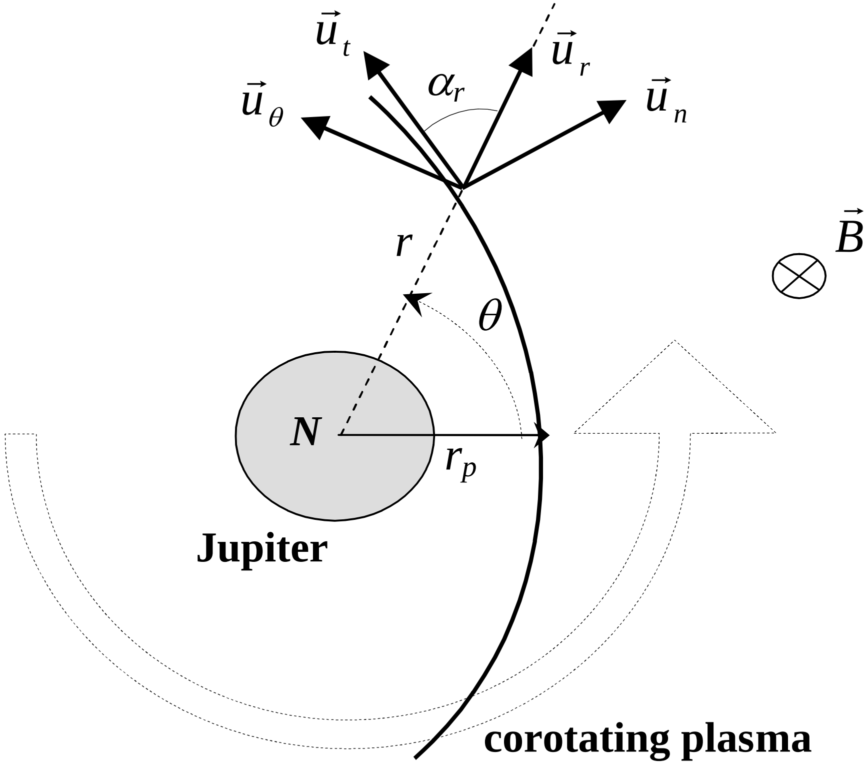
$$\Rightarrow \quad 1 - e_1 = \beta \times (e_h - 1), \quad \beta \sim 1$$

$\Rightarrow$ Use parabolic orbit to calculate capture

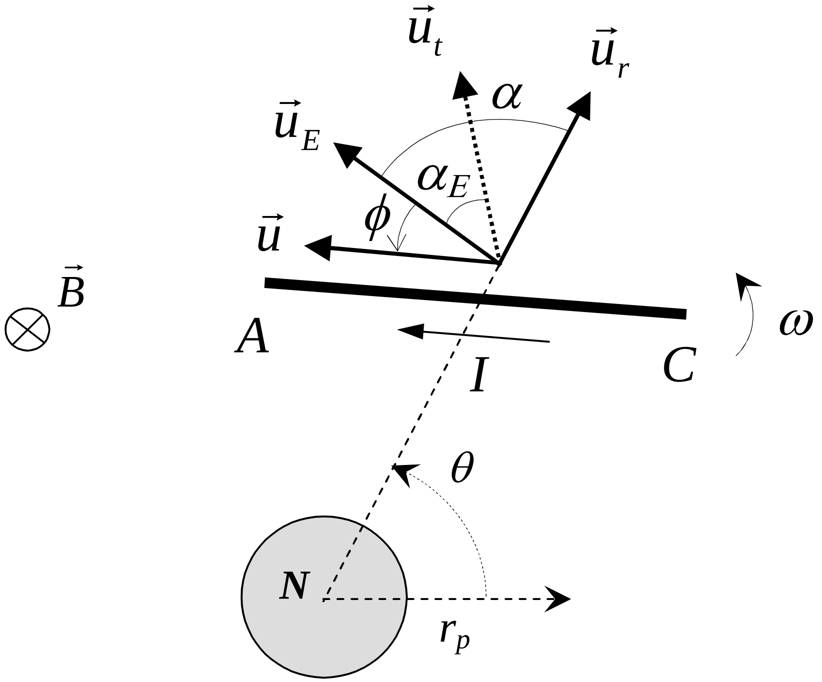
* Assume tether has steady spin (opposite Jupiter spin)

Gravity-gradient torque averages out

* Use no-tilt, no offset dipole magnetic field



Capture under geometry of equatorial parabolic orbit



Unit vectors for motional electric field and spinning tether.

A, C are anodic, cathodic ends. Calculations are φ-averages

Drag work required for S/C capture:

Incoming-orbit energy $\frac{1}{2} M_{S/C} v_\infty^{\ 2} \Rightarrow -\beta \times \frac{1}{2} M_{S/C} v_\infty^{\ 2} < 0$

$$(1+\beta) \times \tfrac{1}{2} M_{S/C} v_\infty^{\ 2} = -W_C \sim L I_{av} B \times r_p$$

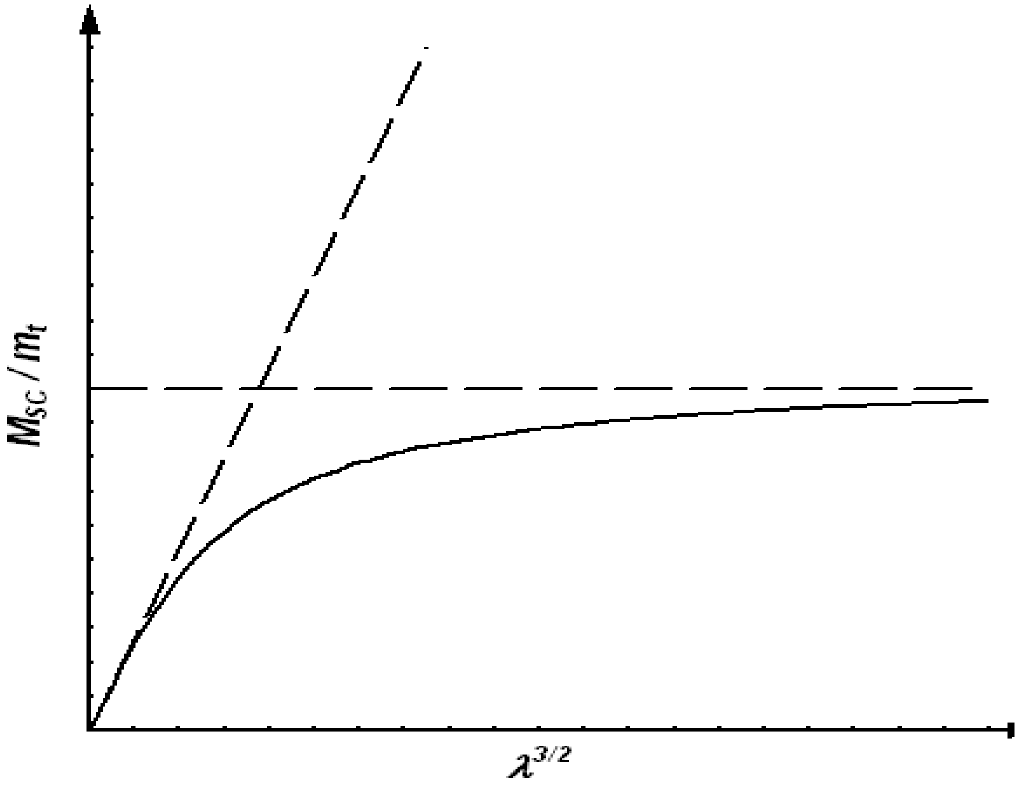
* If no ohmic effects $\left(E_m \equiv \bar{E}_m \cdot \bar{u}\right)$

$$\frac{-2W_C}{m_t v_\infty^{\ 2}} = (1+\beta)\frac{M_{SC}}{m_t} \propto N_e B\sqrt{E_m} \times \frac{r_p}{v_\infty^{\ 2}} \times \frac{L^{3/2}}{\rho_t h} \propto \frac{L^{3/2}}{h}$$

* If ohmic-dominated $\frac{-2\,W_C}{m_t v_\infty^{\ 2}} \equiv (1+\beta)\frac{M_{SC}}{m_t} \propto \frac{\sigma_C B E_m\ r_p}{\rho_t\, v_\infty^{\ 2}}$

Dashed lines: No-ohmic / Ohmic-dominated, bounds on mass-ratio

Solid line: Actual dependence on $\lambda \equiv (L\,/\,50\text{ km}) \times (f_N \times 0.05\text{ mm}/\,h)^{2/3}$



Low λ is case of interest

$$\frac{-2\,W_C}{m_t v_\infty^{\;2}} \;=\; (1+\beta)\times\frac{M_{SC}}{m_t} \;=\; \frac{\sigma_C B_s^{\;2} a_s v_s}{2^{5/6}\rho_t v_\infty^{\;2}}\times S\left(\lambda,\frac{r_p}{R_J}\right)$$

$$\Rightarrow\;\; 2.11\;\times\; S\left(\lambda,\; r_p\,/\,R_J\right)$$

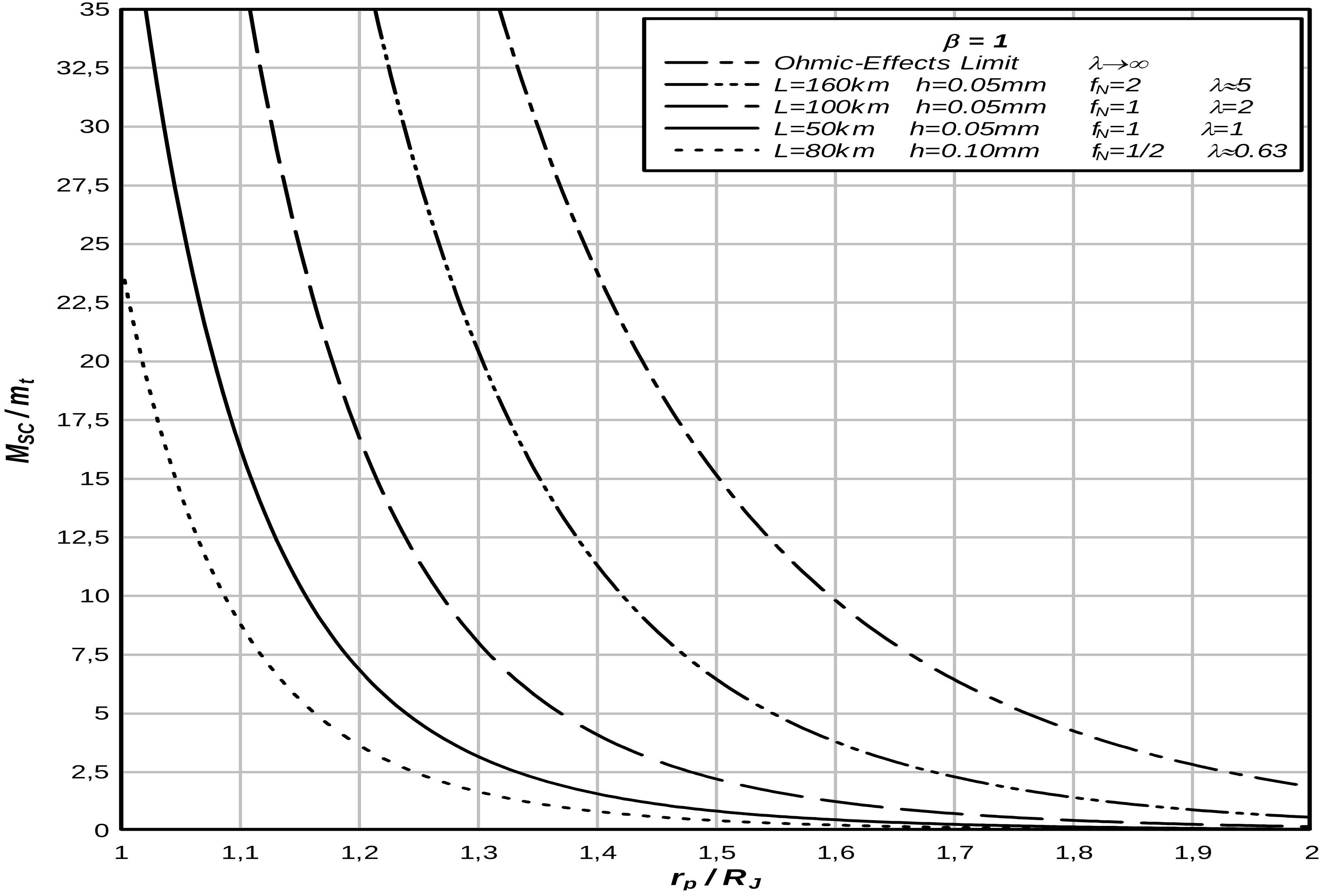
For Al / Hohmann transfer

$\lambda\to\infty$ ohmic-dominated, Low $\lambda \propto L\,/\,h^{2/3}$ weak ohmic-effects

* Performance independent of tape width w. S/C mass scales up with w

Performance depends on plasma density <u>but</u> $S\,(\infty,\,1)\;=\;178$

$\Rightarrow$ Saturn case ($B_s^{\,2}$ smaller by factor ≈ 1/400) needs reduced v_∞


β = 1
Ohmic-Effects Limit λ→∞
L=160km h=0.05mm f_N=2 λ≈5
L=100km h=0.05mm f_N=1 λ=2
L=50km h=0.05mm f_N=1 λ=1
L=80km h=0.10mm f_N=1/2 λ≈0.63
35
32,5
30
27,5
25
22,5
20
17,5
15
12,5
10
7,5
5
2,5
0
1
1,1
1,2
1,3
1,4
1,5
1,6
1,7
1,8
1,9
2
M_SC / m_t
r_p / R_J

Powerful capture (long, thin tape, low perijove)?

* High Lorentz forces, low gravity-gradient forces

($\propto \Omega_{orb}{}^2 = \mu_p / a^3 \propto \rho_p R_p{}^3 / a^3$ for vertical of circular orbit)

$\Rightarrow$ Tether spin ω (opposite Jupiter's) required to keep bowing low

Maximum bowing $\propto \sqrt{L} / \rho_t \omega^2 h$ (greater at lower perijove)

* Tensile stress $\propto \rho_t \omega^2 L^2$ (for given mass ratio)

$\Rightarrow$ too high bowing or too high stress

Bowing $\propto L^{5/2} / h$ (for given maximum stress)

Powerful capture $\Rightarrow$ too hot tether at perijove ?

* Temperature T_t in local equilibrium (too weak diffusivity)

quasisteady equilibrium (too slow tether rotation)

between local / instantaneous radiation loss and heating power

* Local heating power due to impact of electrons dominant at low λ

$T_{t\,max} \propto L^{3/8} / \varepsilon_t^{1/4}$ at anodic end when $\bar{E}_m$ along tether

Relative rise-time $\propto$ $h\omega / L^{9/8} \varepsilon_t^{1/4}$ (smaller at lower perijove)

High emissivity, $\varepsilon_t \sim 0.8$ required

Conclusions

* *Al* tape with $L = 80$ km, $h = 0.05$mm could capture at $r_p = 1.5\, R_J$

a (full) S/C mass up to $5\, m_t$ ($m_t = 216$ kg for $w = 2$ cm)

20 minutes spin, and coating to get $\varepsilon_t \sim 0.8$, satisfy all constraints

Reducing v_∞ below the Hohmann value easies capture.

* Cross section need not be all conductive (weak ohmic effects) $\Rightarrow$

Al /fiber sandwich to reduce ρ_t, prevent tearing, increase tensile strength

* A few MWh extracted at capture $\Rightarrow$ power to use, power to store.