Electrodynamic Tethers for Exploration of Jupiter and its Icy Moons

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** *Galileo* mission: A successful but handcuffed mission

* **GAMs → Waiting period + Protracted trip**

* **Too much chemical propellant, little scientific payload**

* **RTG (and Solar) power sources too weak**

* **Little orbit manoeuvring after capture**

* **Low capability for transmitting data**

Challenge: Fuller exploration of Jupiter and its moons

** **<u>NASA's approach to the challenge:</u>**

* ***Europan Orbiter*** **(National Research Council) /scrapped in 2002**

* **August 2003** ***Aerospace America*** **editorial:**

  → Project ***Prometheus*** **on using NEP**

  Nuclear reactors for power, and for powering e-thrusters

* **Heavy, "unfriendly" systems: 20 - tons** ***JIMO*** **(scrapped)**

  Juno **Polar Jovian Orbiter //** ***Neptune-Triton Vision Mission***

** **<u>ESA's approach to the challenge</u>:**

* ***Jovian Minisat Explorer*** **keeps features of** ***Galileo***

* **From RTG's back to solar arrays:**

→ develop LILT cells with concentrators

* **If failed, reversion to RTG's: problematic;**

Pu 238 oxide scarce, expensive (10^6 € / kg) ; ITAR problem

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

GAMs to get JEO down to Europa in 550 days

**** <u>New approach: Tapping Jupiter's rotational energy</u>**

* **<u>No</u> GAMs, RTG's, solar arrays, chemical propulsion, NEP**

* **Two light S/C; direct trip; "light" tether system**

More scientific payload, data-handling capability

* **Free-lunch, <u>fast</u> manoeuvring (tour)**

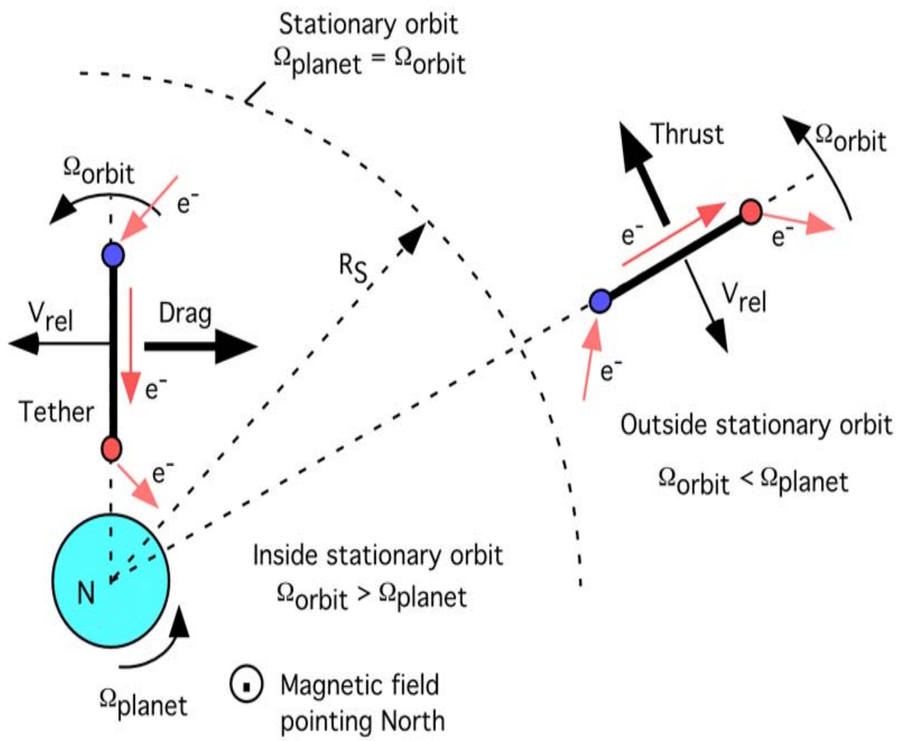
* **S/C capture critical**

Performance dependent on ambient conditions (B, N_e)

* **Model uncertainties: S/C 1 (nominal values), S/C 2 (safety margin)**

** Power generation, Drag, Thrust at an ED Tether

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



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

Inside: $\bar{E}(\textit{tether frame}) = \bar{I} / A\sigma_{cond}$

Lorentz force $L\bar{I} \wedge \bar{B} \quad (\bar{I} \bullet \bar{E}_m > 0)$

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

Thrust <u>if</u> $\bar{v}_{orb}$ **opposite** $\bar{v}_{orb} - \bar{v}_{pl}$

*** Energy ε_{mech} and angular momentum *H* in *planet/light-satellite* system**

$$\varepsilon_{mech}(a) = \frac{1}{2} I_{pl}\,\Omega_{pl}^{\;2} - \frac{\mu_{pl} M_{sat}}{2a},$$

$$I_{pl}\Omega_{pl} + \frac{\mu_{pl} M_{sat}}{a\Omega_{orb}} = const \equiv H_0 > 0, \quad \Omega_{orb} = \sqrt{\mu_{pl}/a^3} > 0$$

*** If** $\frac{4}{3^{3/4}} \times I_{pl} \sqrt{\frac{\mu_{pl}}{(I_{pl}/M_{sat})^{3/2}}} < H_0$

$\varepsilon(a)$ presents *maximum / minimum* with rigid-body motion ($\Omega_{pl} = \Omega_{orb}$)

*** Maximum is unstable under dissipation (tidal, air-drag, ED-tether)**

For M_{sat} small enough (artificial satellite) $\rightarrow$ $a(max) = a_{st}$

*** Drag in westward LEO but thrust if $a > a_{st}$ in eastward LEO**

(*Alfven*'s interplanetary engine concept involved no ε_{mech}-maximum)

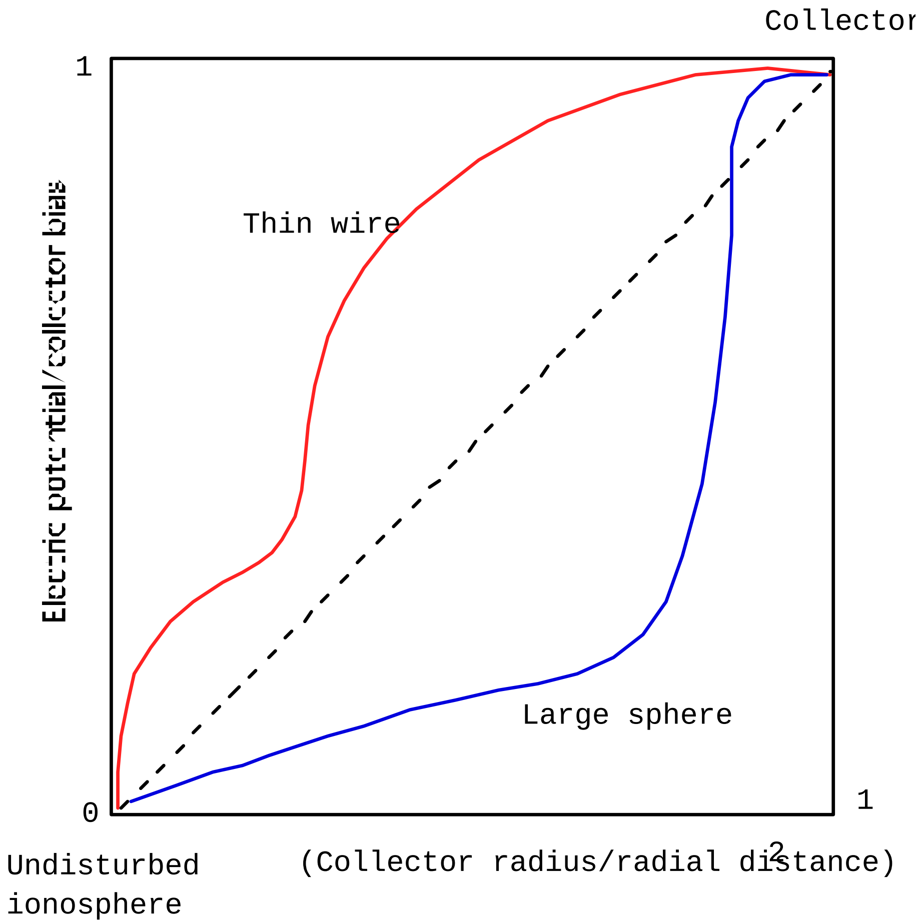
**** Tether consumes little expellant at Hollow Cathode**

HC's reach $I_{hc}/\dot{m}_{hc} \approx 10^2$ A / mg s^{-1} (*charge/mass* ratio of proton)

$$\frac{Lorentz\ force}{\dot{m}_{hc}} \sim L \times \frac{I_{hc}}{\dot{m}_{hc}} B \approx 10{,}000 \frac{km}{s} \times L(km) \times B(gauss)$$

*** Compare to rocket (electric) thruster:** $\frac{Thrust}{\dot{m}_{prop}} \equiv g_0 \times I_{sp} \sim 3\ (30)\ \frac{km}{s}$

** A (thin) tether itself, if left bare, collects electrons efficiently



$$I \rightarrow I_{av}$$

No effective potential barrier

$\Rightarrow$ No space-charge effect

*** Also, no magnetic effects**

*** Tape collects same current,**

is lighter than round wire

of equal lateral surface

** <u>The Jupiter free-lunch tour</u>

* The synchronous (stationary) orbit lies at $a_{st} \approx 2.24\ R_J$

  (elliptic orbits modify condition $a <$ or $> a_{st}$ for drag or thrust)

* Drag/Thrust only applied well within plasmasphere

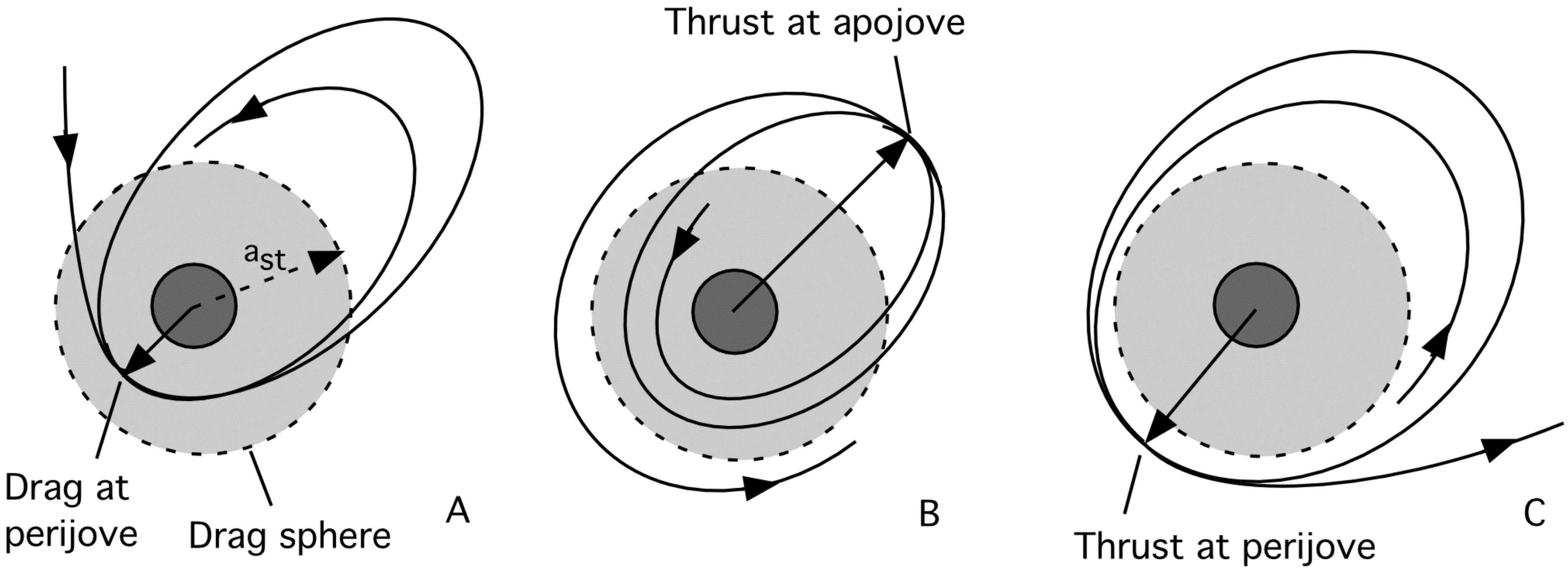
* Current shut off at convenience

* Tether used as power source (plug in electric load)

* S/C approaches with relative velocity $v_\infty \sim 5.7$ km/s,

  perijove at $r_p \sim 1.5\ R_J \quad \rightarrow \quad e - 1 = v_\infty{}^2 r_p / \mu_J \approx 0.027$

* After capture, closed orbits evolve under repeated Lorentz force



A: Capture / Lowering apojove. B: Raising perijove.
C: Raising apojove / Escape

*** Phase A: Best perijove for capture, best final apojove ?**

*** Ph. C: Perijove? 2/3, ¾ resonances with *Io* at 3.10 R_J, 3.84 R_J**

*** Raise apojove of S/C 1 to *Io***

use Lorentz thrust by fast-flowing *Io* torus

to accelerate S/C 1 to *Io*'s velocity → capture

*** Raise S/C 2 apojove to *Io*;**

use torus thrust to raise perijove to *Io*

Next, raise apojove to *Europa*?

escape back to *Earth*?

**** Capture over drag path $\sim \pi\, r_p$ sets mass-ratio condition**

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

$$I_{av} = \frac{2}{5} \times \frac{2wL}{\pi} \times eN_e \times \sqrt{\frac{2eE_m L}{m_e}}$$

$$\frac{M_{SC}}{m_t} = \frac{8\alpha}{5(1+\beta)} \times \frac{m_e N_e r_p}{\rho\, h} \times \frac{\sqrt{2eE_m L / m_e} \times L\, eB / m_e}{v_\infty^{2}} = 4$$

*** $N_e \approx 10^3$ cm^{-3}, B ≈ 1.6 gauss, $E_m \approx 4.8$ V/m at $r_p = 1.5\, R_J$**

***Al* tape, thickness $h = 0.05$ mm, L = 50 km, $\alpha = 0.5$, $\beta = 3/4$**

Width w = 2cm $\Rightarrow$ m_t = 135 kg, M_{SC} = 540 kg, I_{av} = 11.9A

* **Phase A**

$$\frac{1}{2}v_{hp}^{2}-\frac{\mu_J}{r_p}=\frac{1}{2}v_{\infty}^{2}\ \rightarrow\ \frac{1}{2}v_{1p}^{2}-\frac{\mu_J}{r_p}=-\beta\,\frac{1}{2}v_{\infty}^{2}\equiv-\frac{\mu_J}{2a_1}$$

$$\frac{1}{2}v_{2p}^{2}-\frac{\mu_J}{r_p}=-(1+2\beta)\,\frac{1}{2}v_{\infty}^{2}\equiv-\frac{\mu_J}{2a_2},\ \ldots$$

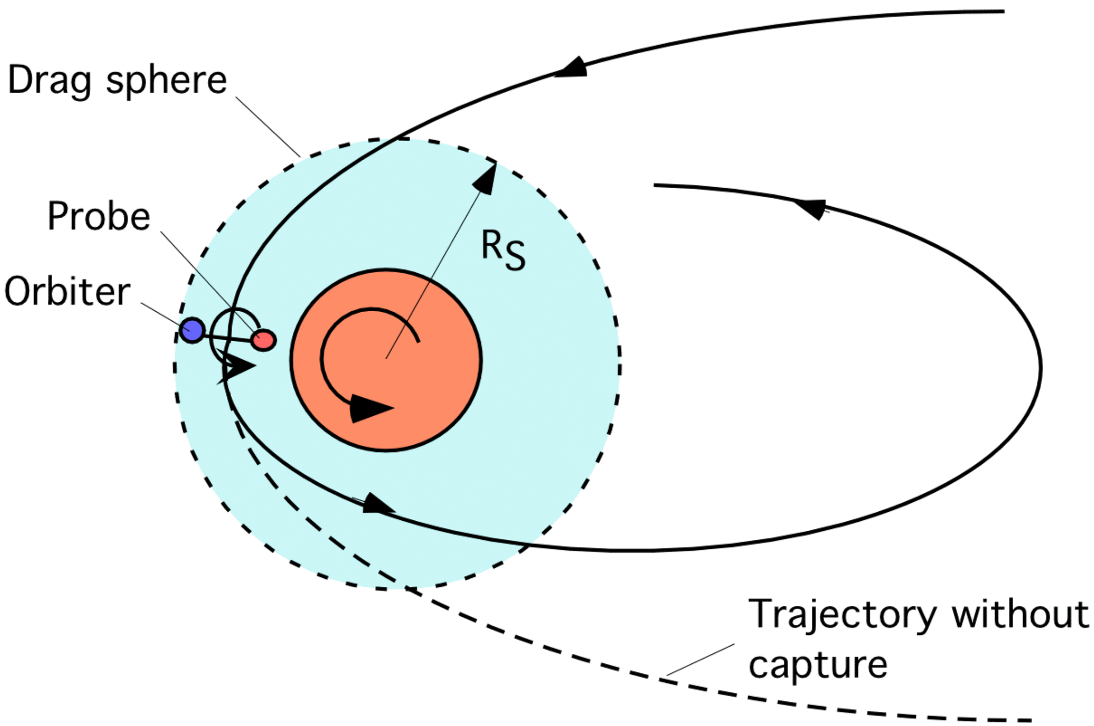
$\frac{\mu_J}{v_{\infty}^{2}a_n}=n-1+n\beta\ \rightarrow$ **a_1 = 72.8 R_J, T_1 = 76.5 d; a_3 = 12.8 R_J, T_3 = 5.6 d**

* **Thermal issues? // Power generation? // Radiation survival?**

* **From $I_{av}E_mL$ = 2.86 Mw, ~ 30 Kw extracted at electric load**

* **Expellant used in phase A, $m_{hc}\sim M_{SC}\times v_p/(LBI_{hc}/\dot{m}_{hc})\sim 10^{-4}M_{SC}$**

* **Orbital/tether dynamics? Because of the low gravity gradient, tether spun when deployed by end thrusters**



A 20 minutes period spin provides tether tension and gyroscopic stability

The spin also produces a Δv between tether tips

that might be exploited to release a probe to visit a Jovian moon

* **<u>Phase C</u>**

Raise S/C to circular orbit at 3.84 R_J

With perijove at 3.84 R_J raise apojove to *Io*'s orbit at 5.9 R_J

Hohmann transfer velocity,

$$v_a = v_{Io} \times \sqrt{\frac{2\,r_p}{r_p + a_{IO}}}\ 0.89\,v_{Io} \qquad (v_{Io} << \Omega_J\, a_{Io})$$

Inside the dense *Io* torus fast rotating at Ω_J

(outside Io's small sphere of influence (radius 7200 km, R_{Io} = 1820 km)

use Lorentz thrust to increase the apojove velocity (raising perijove)

*** After few apojove passes, *Io* may capture S/C at a few kms altitude**